A FEASIBILITY STUDY OF NATURAL VENTILATION IN A MIDRISE STUDENT DORMITORY BUILDING

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ABSTRACT

This study investigates the feasibility of utilizing natural ventilation through operable windows to provide ventilation and summer cooling for an existing university dormitory building in marine west coastal climate (warm summer and mild winter). A hybrid research approach is used to evaluate the performance of proposed natural ventilation schemes, featuring building energy modeling with fully integrated airflow network, onsite blower door tests, and building utility data analysis. Both ventilation and thermal comfort are studied during the investigation. Simulation results demonstrate great potential of relying on properly controlled operable windows to supply ventilation and maintain indoor thermal comfort.

INTRODUCTION

In today's climate of sustainable design, engineers in every discipline are focusing on optimizing system efficiency. The area of building design is no exception. High occupancy buildings, such as office buildings and dormitory buildings, are notorious energy consumers, where the heating, cooling, and air conditioning system (HVAC) has been known to consume the most energy compared to any other building systems (DOE 2009). A large number of energy efficiency measures are proposed to reduce their energy consumptions. Natural ventilation, also called hybrid ventilation when mechanical assistance is used, is one of the most efficient and economic measures given the right ambient condition (BRECSU 2000). Operable windows are one convenient way to introduce natural ventilation into living spaces, especially for buildings with sufficient perimeter zone access. The term operable window simply refers to a window that is able to open and close; as opposed to exterior glazing windows which are non-operable and serve mainly as an aesthetic feature and daylight source. The use of operable windows has been shown to reduce the annual energy consumption in high occupancy buildings when properly configured and controlled. Meanwhile improper control of operable windows can also significantly increase the energy demand of the HVAC system (Daly 2002).

The critical issue in designing a natural ventilation system is the control algorithm. The magnitude of the airflow rate through operable window varies widely depending on building geometries, ambient temperature, wind speed, and direction. The design challenge is to control window openings as a function of the ambient environmental condition so that the incoming airflow brings an acceptable amount of fresh air to sustain indoor environment in terms of both ventilation and thermal comfort.

The objective of this study is to investigate the feasibility of using natural ventilation through operable window to sustain both ventilation requirements and thermal comfort in midrise dormitory buildings in the mild marine west coastal climate. An existing institutional dormitory building, where each dormitory room has at least one operable window, is used as a case study. The control algorithm investigated in this study is the classic temperature based control where the degree of window opening is proportional to the temperature difference between indoor air and ambient air. Ventilation and thermal comfort are the two primary performance aspects that this study investigates.

METHODOLOGY

Simulation Environment

EnergyPlus is a leading building energy simulation tool on the market (Crawley et al. 2000) and is chosen as the simulation software package of this study for several reasons. First, recent improvements to EnergyPlus allows the airflow model and the energy model to be fully integrated (Gu 2007). This avoids the complication of modeling natural ventilation and its impact to building energy performance in coupled simulation environments, such as EnergyPlus and COMIS (Mehta 2005), TRANSYS and CONTAM (McDowell et al. 2003), etc. Second, EnergyPlus provides built in support for weather data as well as wind pressure coefficient data from external sources.

Hybrid Approach to Model Development

This study uses a hybrid approach for model developments. Utility data, field measurements, and third party tools are used in order to develop a representative model to estimate the natural ventilation rate through operable windows in a midrise institutional dormitory. Figure 1 shows a simplified flowchart of this approach. Utility data are collected to provide an estimate of internal gains in the dormitory building; blower door tests are conducted to estimate natural ventilation model parameters for operable windows; and third party tools are used to estimate wind pressure coefficients of building facades. Details of each component are presented in the case study section.



Figure 1 A Simplified Methodology Flow Chart

Performance Indicators and Evaluation Criteria

Natural ventilation is investigated from two performance aspects in this study: ventilation and thermal comfort. The performance of the temperature based window control algorithm is evaluated based on thermal comfort and ventilation criteria set forth by the corresponding ASHRAE standards.

Ventilation performance is gauged by calculating the number of hours that the minimum ventilation rate requirement is not met. The minimum acceptable ventilation rate is set to be 0.007 m³/s (15 CFM) per person by ASHRAE 62.1-2004 (ASHRAE 2004). A zone is considered to be under-ventilated if the argument in Equation 1 is true.

$$Q_{zone} < N_{occupants} Q_{required}$$
 (1)

Where, Q_{zone} is the zone ventilation rate, $N_{occupants}$ is the number of occupants in the zone, and $Q_{required}$ is the ventilation requirement per person from ASHRAE 62.1-2004.

The indoor thermal comfort performance is measured by calculating the number of both hours and degreehours that each zone is overheated. Figure 2 shows the acceptable indoor temperatures in a naturally ventilated space. The temperature range corresponding to the 90% acceptability limits is used in this study, i.e. 90% of the occupants should feel comfortable if natural ventilation manages to regulate indoor temperature within this range. The acceptable temperature range is determined on a monthly basis. For example, if the average temperature for the month of August is 20°C, the acceptable temperature range is between 21.5°C and 26.5°C. A zone will be considered as being overheated if its temperature rises above the 26.5°C in August at a given time step.

The total over-heated degree-hours (OHDH) are calculated using Equation 2,

$$OHDH = \sum t_{OH} (T_{zone} - T_{upper \, limit}) \qquad (2)$$

where, OHDH is the over-heated degree-hours, t_{OH} is equal to the length of the time step, T_{zone} is the zone operative temperature at each time step, and $T_{upperlimit}$ is the upper limit of acceptable temperature from ASHRAE 55-2004.



Figure 2 Acceptable Operative Temperature Range for Naturally Conditioned Spaces (ASHRAE 55-2004)

CASE STUDY MODEL DEVELOPMENT

Building description

The case study building is a ten story student dormitory building consisting of 8 floors of student dormitories, 1 floor of office and classroom space, and 1 floor of retail which occupies the sidewalk level. Figure 3 shows a representative floor plan of the eight dormitory floors. The building, known as the Broadway Housing Building (BHB), is located in Portland, OR on the Portland State University campus. The BHB is a LEED Silver building and was first occupied in 2005. The climate in Portland, OR is classified as marine west coastal climate (Peel et al. 2007) which is well suited for the use of natural ventilation due to its mild winters and warm (as opposed to hot) summers. A previous study found that 98% of the yearly cooling load can be met using natural ventilation in this particular climate (Axley 2001). The weather patterns do not vary much from day to day, and temperature extremes are rare and short-lived. Table 1 shows summer ambient temperature statistics for Portland based on the typical meteorological year (TMY) weather data set used in EnergyPlus (Wilcox and Marion 2008).

The BHB's L-shaped floor plan consists of 49 naturally ventilated dormitories connected by a common access corridor, which is mechanically ventilated and conditioned year-round. Each dormitory is intended to house a maximum of two individuals. The typical dormitory layout consists of one bathroom and one large living space totaling about 28 m² of floor area.

	AVERAGE TEMP (C)	MAXIMUM TEMP(C)	MINIMUM TEMP(C)
JUN	17.6	33.3	9.4
JUL	19.9	37.8	12.2
AUG	20.1	36.7	11.1
SEPT	17.3	33.3	7.2

 Table 1

 Summer Temperature Statistics for Portland OR

The dormitories are designed to be ventilated through one operable window in conjunction with continuous (no occupant control) bathroom exhaust. The operable window provides ventilation air even when it is closed due to the "leakiness" associated with exterior walls and window frames. The exhaust fan creates a negative pressure, which induces inter-zonal flow through cracks in the door that connects to the corridor, and thereby draws a certain amount of conditioned air into the dormitory from the corridor. Except for those on the corners of the building, each dormitory has only one exterior wall and one operable window. Every dormitory is equipped with a baseboard heater controlled by a wall-mounted thermostat. There is no mechanical cooling system in the individual dormitory.



Figure 3 BHB Floor Plan

Physical Measurements

The model developed for this case study is constructed using a combination of architectural drawings and onsite measurements.

A standard blower door test is performed that measures the infiltration leakage area (at 50 Pascals) of a typical (non-corner unit) BHB dormitory that has one exterior wall. This data is used to estimate the effective leakage area for each external wall in the BHB.

The blower door equipment is then used to induce and measure the airflow through an open window as well as the pressure difference across the opening. Tests are conducted at 25, 50, and 75 Pascal pressure differences and then averaged. This allows the area and discharge coefficient to be measured simultaneously. Equation 3, which is developed using the Bernoulli Principle, shows this relationship. This method is advantageous because the window opening area is very difficult to measure accurately alone. In addition, the discharge coefficient of the window assembly is very difficult to measure once installed on the façade and is likely to change with the window position. The quantity A_WC_d is used as input for the airflow model to calculate the volumetric flow rate through the window. Repeating this process at four window positions (5°, 10°, 15°, and the maximum 20°) characterizes the window across the complete range of opening positions. The results from both the standard and modular window blower door test are summarized in Table 1.

$$A_W C_d = 10\ 000 Q \sqrt{\frac{\rho_{air}}{2\Delta P}} \tag{3}$$

where A_W is the window area (cm²), C_d is the discharge coefficient (unitless), Q is the volumetric flow rate through the window (m³/s), ρ_{air} is the density of air (kg/m³), and ΔP is the pressure difference (Pa).

Table 2 Blower Door Test Results

	AREA*CD AT OPENING ANGLE				
	(CM^2)				
PRESSURE	0	5	10	15	20
DROP (PA)					
25	N/A	13.6	33.1	56.4	70.8
50	4.0	12.5	33.2	57.9	81.0
75	N/A	12.2	34.4	N/A	N/A
AVERAGE	4.0	12.7	33.6	57.1	75.9

Model of Airflow Network

A multizone airflow network model is developed in EnergyPlus that includes all airflow paths, such as doors, windows, exhaust fans, and effective leakage areas (ELAs). The multizone model calculates airflow based on the pressure-flow characteristics of each flow path. The airflow network model is verified by intermodal comparison with CONTAM, a well known multizone airflow and contaminant transport analysis software (Walton and Dols 2006). The important components of the multizone airflow model include the infiltration model of the dormitory, the operable window model, and the wind pressure coefficient (to be addressed in the following section).

The infiltration of individual dormitories is modeled using an

AirflowNetwork:MultiZone:Surface:EffectiveLeakageArea

object in EnergyPlus. The measured ELA value and reference pressure at which the blower door test is conducted (shown in Table 2) are used to calculate infiltration flow rate of each typical dormitory. The ELA value of corner dormitories with more than one exterior wall is estimated based on the measurement done for the typical room but adjusted to reflect increased infiltration due to larger exterior façade area. A simple linear relationship between the ELA and exterior façade area is assumed for the adjustment. The door that connects each dormitory to the corridor is modeled using the equivalent of the ASHRAE best estimate for a single, not weatherstripped, internal door (ASHRAE 1997).

EnergyPlus has four built-in window ventilation control algorithms: NoVent, Temperature, Enthalpy, and Constant. This study uses the temperature based control. Windows open when the indoor temperature is higher than the cooling setpoint and also higher than outdoor temperature. The opening factor, a parameter with value between 0 and 1, is calculated by the algorithm and then multiplied with the opening area to represent different window openings. The algorithm is based on two temperature difference limits. The lower limit defines the point below which the opening factor stays constant at 1 (i.e. window stays at the maximum opening). The upper limit is the point beyond which the opening factor is 0 (i.e. window stays closed). Opening factors at other temperature difference points between the two limits are calculated by interpolation. Figure 4 shows a graphical representation of this control algorithm. A parametric analysis is performed in EnergyPlus to determine what the temperature limits result in the fewest number of over-cooled degree-hours during the shoulder months of June and September. The lower limit of 5°C and upper limit of 20°C are used in this study.



Figure 4 - Window Modulation Algorithm (EnergyPlus)

The operable window is modeled using the AirflowNetwork:MultiZone:Surface:DetailedOpening object in EnergyPlus. It allows users to specify opening area and discharge coefficient data at up to four different opening positions indicated by opening factor. Given the opening factor determined by the temperature control algorithm, EnergyPlus calculates the corresponding opening area and discharge coefficient by interpolation.

Another important characteristic of the BHB's hybrid system is that the HVAC system in the corridor supplies the make-up air that is extracted by the exhaust fans installed in the bathroom of each dormitory. This results in a positive pressure in the corridor zone relative to individual dormitories and will influence the inter-zonal flow through door cracks. Since the corridor is mechanically conditioned this air exchange will also bring certain amount of cooling to the dormitory and is important to capture in detail in the airflow model. The bathroom exhaust fan in each dormitory is modeled using the ZoneExhaustFan object in EnergyPlus, and the exhaust airflow is assumed to be $0.0094 \text{ m}^3/\text{s}$ (20) CFM) according to ASHRAE 62.1-2004 guidelines (ASHRAE 2004). The positive pressure in the common corridor is modeled by adding leakage in return duct using the the AirflowNetwork:Distribution:Component:LeakageRatio object in EnergyPlus. The leakage ratio is adjusted so that the surplus air (i.e. the difference between supplied air and returned air) of the corridor zone is equal to the number of exhaust fans multiplied with the continuous flowrate of 0.0094 m^3 /s (20 CFM).

Wind Pressure Coefficients

Wind pressure is one of the most important boundary conditions in natural ventilation modeling. It is also very difficult to predict for buildings with complicated shapes located in dense urban environments. Equation 4 shows the wind pressure model used in EnergyPlus. The challenging issue is to determine the wind pressure coefficients along the length and height of the external façade.

$$p_{wind} = C_p \rho \frac{v_{ref}^2}{2} \tag{4}$$

where, p_{wind} is the wind pressure exerted on a surface, C_p is the dimensionless wind pressure coefficient, ρ is the density of the airstream, and V_{ref} is the velocity of the airstream.

As an alternative to developing a full CFD model or conducting wind tunnel experiments, an application external to EnergyPlus is used to estimate the wind pressure coefficients along the building's exterior surface. This program, called Cp Generator, uses developed algorithms based specially on systematically performed wind tunnel tests and published results of on-site tests to predict wind pressure coefficients (Knoll et al. 1995). It has been validated by several different research projects over the course of 20 years (Costola et al. 2009). Cp Generator also accounts for wind shielding by local obstacles, which makes it particularly useful for the BHB case, since it is located in a fairly dense urban environment.

Figure 5 shows a map of the BHB's neighborhood. Buildings that fall within the suggested radius of 5 times the BHB's height are included as obstacles in the Cp Generator model. The C_p values at each external node of the BHB, namely each window and external wall, are estimated by the Cp generator simulation in 10-degree increments. Figure 6 shows sample wind pressure coefficients at the center of each façade on the west wing of the BHB. The wind direction is measured clockwise from the North.



Figure 5 - BHB Neighbourhood Map



Figure 6 Sample Wind Pressure Coefficient Output from Cp Generator

Building Energy Model

The building energy model of BHB is developed in EnergyPlus in conjunction with DesignBuilder (Tindale 2005). DesignBuilder is a detailed building energy analysis tool using EnergyPlus as the enhances simulation engine. DesignBuilder EnergyPlus by providing a 3-dimensional Graphic User Interface (GUI) that allows users to build the building geometry quickly and easily. A detailed floor plan of BHB is built up in DesignBuilder first, including all partitions, windows, and doors. The geometry model exported from DesignBuilder is then continuously modified in EnergyPlus to better represent the actual BHB. Unique features of the energy model include modeling only one floor at a time assuming no heat transfer through the floor and ceiling, and to use the electricity meter data to estimate internal gains.

An HVAC system is assigned to the corridor where the cooling setpoint is set to be 24°C. The energy balance of the corridor is not studied in depth in this case because the sole interest is the ventilation performance through operable windows. The model simply attempts to include the conditioned corridor in order to build realistic boundary conditions and capture its interaction with the dormitories through door cracks. The individual dormitories are equipped with electric baseboard heaters with a heating setpoint of 20°C.

Due to the use of certain features in the airflow model and limitations of EnergyPlus, the BHB energy model can only model one floor at a time. It is assumed that vertical heat conduction between floors is negligible due to the very small zone temperature difference. This assumption is justified using CONTAM by quantifying the difference in air flowrate entering a zone due to elevation differences. The heat gain/loss associated with the variation in air flowrate is then compared to the overall heat gain/loss through the zone's envelope and found to be negligible. This suggests that if two zones, one above the other, are controlled by the same temperature algorithms, the temperature difference between them will be very small and heat conduction between them through the floor/ceiling will be nearly zero and therefore can be neglected.

Internal gains are one of the most widely varying parameters associated with occupant behaviour. Every occupant's habits and schedule are likely to vary from one to another. Historical power meter data are used in this study to develop an average monthly consumption profile. It is assumed that 100% of the electrical energy consumed is emitted into the dormitory as internal gains.

Every dormitory has a small refrigerator that cycles continuously throughout the summer. This internal gain is implemented in EnergyPlus using an ElectricalEquipment object and is not dependent on occupancy. After subtracting the refrigerator's load from average monthly profile, the remaining internal gains such as plug loads and lighting are implemented in EnergyPlus using the Lights object and correspond to the occupancy schedule. An occupancy schedule for a university bedroom, developed by the UK National Calculation Method, is adopted in this study to represent the number of occupants at any given time of day (NCM 2009).

RESULTS

The performance of natural ventilation through operable windows in BHB is evaluated for the extended summer season from June 1st to September 30^{th} . The TMY3 weather data from Portland, OR International Airport is used for the case study. For the sake of brevity, only the 7th floor (the middle floor of the dormitory floors in BHB) of the BHB is analyzed and discussed in detail in this section.

Ventilation Performance

Figure 7 shows the floor plan mapped with the average ventilation rate for each dormitory zone for the 4 month simulation period. The zone average ventilation rate ranges from 0.027 to 0.112 m³/s and the floor average is 0.048 m³/s. It is noted the average ventilation rate for individual dormitory zone

is well above the ASHRAE specified ventilation rate of 0.014 m³/s for the maximum occupancy of two. The corner zones, which have more than one operable window, show significantly higher ventilation rates. This is especially true for the northwestern corner zone as well as other northern corner zones. This is due to the fact that the predominant summer wind blows from the North-West in Portland (WRCC 2011).





Under-ventilated hours are estimated by counting the total number of hours each zones falls below the minimum ventilation rate, specified in Equation 1. Figure 8 shows the distribution of under-ventilated hours by zone. The north-western corner zone shows the fewest number of hours under-ventilated. This result is expected due to the much higher average ventilation rate observed in Figure 7 for that zone. The building as a whole shows very few hours of under ventilated hours range from 11 to 101 hours. The average for the 7^{th} floor is 48.7 hours, which represents 1.6% of the simulated summer hours and 3.4% of the occupied hours.

Figure 9 shows the distribution of flow rates when a zone is under ventilated versus the percentage of total under ventilated hours. This is one way of gauging the magnitude of under ventilation that is likely to occur. It is shows that for 90% of the time when zones on this floor are under ventilated, the ventilation rate exceeds $0.0071 \text{ m}^3/\text{s}$, the minimum rate for one occupant. This means that a given zone is almost always adequately ventilated for at least one person.



Figure 8 Hours Under Ventilated by Zone



Figure 9 Distribution of Under Ventilated Flow rates

Thermal Comfort Performance

The thermal performance of the proposed control system is investigated by comparing simulated zone operative temperatures against the acceptable temperature range for naturally ventilated spaces specified in ASHRAE 55 standard. The total number of hours and degree-hours that exceed the upper limit are calculated for each zone over the simulation period. In terms of occupant comfort, these performance indicators predict how long a zone will be uncomfortable (hours overheated) as well as how far the zone is outside the comfort range (degree-hours overheated).



Figure 10 Degree-hours Overheated by Zone



Figure 11 Hours Overheated by Zone

Figure 10 and Figure 11 show the floor plan mapped with the total number of overheated degree-hours and overheated hours, respectively, for each zone over the course of the summer. The overheated degreehours range from several zones with zeros to a maximum of 112 °C-hrs. The average for the 7th floor is only 19.1 °C-hrs. The overheated hours range from 0 to 99 with an average of 29.7. By dividing the total number of overheated degree-hours by the overheated hours for a specific zone, the average degree of overheating can be calculated. As an example, the north-west corner would be, on average, overheated by 1.3°C (127 °C-hrs / 96 hr) for 96 hours over the investigated period. The north-western corner zone is by far the worst in terms of thermal comfort. Its exposure to the prevailing north-western winds and large exterior wall area make it vulnerable undesirable and uncontrolled infiltration. to However, 127 degree-hours over the course of 4 summer months is fairly low and should still be acceptable to most occupants. The results also show that the dormitories along the western façade are overheated well above average. This can be explained by their exposure to the afternoon sun. Appropriate shading strategies could be investigated

and implemented to the west façade to improve the thermal comfort performance of dormitory rooms in this wing.

Entire Building Performance

Table 3 summarizes average ventilation rate, average under-ventilated hours, average number of overheated hours, and average overheated degreehours per each floor over the extended summer period for the entire BHB. Results show that the BHB, on average, is adequately ventilated by natural ventilation through operable windows, and is overheated for about 1% of the investigated summer period with average overheated degree-hours of 14.9.

Table 3					
Simulation Results for the Entire Building					
AVEDACE		OVED			

	AVERAGE		OVER-	
	VENT	UNDER	HEATED	OVER-
	RATE	VENTED	DEGREE-	HEATED
FLOOR	(M ³ /S)	HOURS	HOURS	HOURS
3	0.0403	43.3	20.0	34.3
4	0.0420	45.5	19.6	32.6
5	0.0436	47.0	19.3	31.5
6	0.0453	49.5	19.1	30.8
7	0.0461	49.2	19.1	30.3
8	0.0469	51.4	19.1	30.1
9	0.0476	51.4	18.9	29.4
10	0.0483	50.6	18.9	28.9

CONCLUSION

This study investigates the feasibility of natural ventilation through operable windows in providing ventilation and summer cooling in an existing midrise student dormitory building in the mild marine west coastal climate. A comprehensive building energy model, fully integrated with an airflow network model, is developed using a hybrid approach. Onsite blower door tests are conducted to quantify the flow characteristics of infiltration through exterior façade and operable windows. Utility data are used to quantify the actual internal gains in the building. Results show that operable windows, controlled by a simple temperature based algorithm, are able to provide sufficient ventilation during 98.4% of the summer time (June to September) and reduce the average overheated degree hours for the entire building to 14.9°C-hrs. Future work will focus on the investigation of realistic controllers that could be easily implemented for each window and better respond to both ambient temperature and dynamic wind conditions.

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