Proceedings of BS2013:
13th Conference of International Building Performance Simulation Association, Chambéry, France, August 26-28

HUMAN-BEHAVIOR ORIENTED CONTROL STRATEGIES FOR NATURAL VENTILATION IN OFFICE BUILDINGS

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ABSTRACT

Natural ventilation is a cost-effective way to reduce cooling energy for buildings. However, the performance of natural ventilation largely depends on outdoor climate. A good and feasible control strategy is the key to ensure high performance of natural ventilation. Typically, windows are operated by occupants. Therefore, a control strategy that based on human behavior can enhance the performance of natural ventilation. This paper studied four different control strategies that simulate human behavior based on temperature and humidity in a climate with high outdoor humidity. The results showed that human behavior based control strategy can largely reduce the high humidity hours during occupied hours while only slightly increases air temperature.

INTRODUCTION

Building energy consumes 2/3 of the electricity in the United States and the significant of the electricity consumption is for summer cooling. Natural ventilation has a large potential to reduce cooling energy for many regions in the United States. However, the performance of natural ventilation is largely depended on outdoor climate. Active control on natural ventilation is needed to ensure best cooling performance in summer. Previous studies on control strategies for optimizing natural ventilation performance involved complicated control based on various parameters or even future temperature (Spindler and Norford, 2009; Menassa et al., 2013; Van Paassen et al., 1998). The control strategies are only suitable for automation system and will increase the initial cost. Furthermore, simulation based on such control strategy will often results in large discrepancy with onsite scenario (Roetzela et al. 2010), which is believed to be the discrepancy of control strategies in actual case and in simulations.

Since most existing buildings do not have automated windows, only the occupants can operate the windows. This type of buildings posed two restrictions on the control: 1) window cannot be operated when the space is unoccupied, such as during night-time; 2) the window operation should be based on the sensation of human.

Recently, some researchers have purposed models that are based on human behaviors for natural ventilation control (Yun et al., 2008a; Yun et al., 2008b). Those models were derived from field studies that considered indoor temperature, time of the day and the previous state of the window (e.g. window was already opened or closed). The results showed a large scattering from different field observations because each person's sensation to the environment and the criteria to open the window were different. Moreover, other parameters such as indoor air quality (IAQ) and humidity are also important for the occupants to decide whether to open a window or not.

This study investigated four control strategies that are oriented by humidity, ventilation hours and temperature. The strategies represent different typical human behaviors and are suitable for different climates and building types. We conducted numerical simulations of natural ventilation performance with the control strategies for a small office building in Philadelphia by using typical meteorological year (TMY3) weather data. Thermal comfort was calculated with the adaptive model from ASHRAE Standard 55-2010, relative humidity and ventilation hours.

SIMULATION

This paper used the single-sided wind-driven model from Wang and Chen (2012) and modified it to include the buoyancy effect for calculating the ventilation rate. The pressure difference between indoor and outdoor at height "z" along the opening is calculated based on the wind pressure difference across the opening and the stack pressure due to different indoor and outdoor temperature, as shown in Eq. (1)

$$\Delta\bar{P}(z) = \frac{1}{2} C_p \frac{\bar{U}^2}{z_{ref}^{2/7}} \left(z^{2/7} - z_0^{2/7} \right) - \rho_i g (z - z_0) \frac{T_i - T_o}{T_o} \quad (1)$$

The neutral level is an additional unknown which can be calculated based on the mass balance between incoming and outgoing ventilation rate through the opening as:

$$\bar{Q} = \bar{Q}_{in} = \bar{Q}_{out} \quad (2)$$

$$\bar{Q} = C_d l \int_{z_0}^{h_2} \sqrt{\frac{2\Delta\bar{P}(z)}{\rho_{out}}} dz = C_d l \int_{h_1}^{z_0} \sqrt{-\frac{2\Delta\bar{P}(z)}{\rho_{out}}} dz \qquad (3)$$

The above equation system can yield mean ventilation rate. Due to the pulsating flow and eddy penetration in single-sided ventilation, fluctuating ventilation rate is very important. The contribution from pulsating flow is calculated as

$$\sigma_{q_p}{}^2 = \left(C_d l \frac{1}{z_{ref}{}^{1/7}} \sqrt{C_p} \int_{z_0}^{h} \sqrt{z^{2/7} - z_0^{2/7}} dz \right)^2 \sigma_u{}^2 \qquad (4)$$

where σ_u is assumed to be 10% of the mean wind velocity. The eddy penetration can only occur when the eddy scale is smaller than the opening scale. By applying the spectrum analysis on the wind velocity, the energy of the penetrated eddy can be calculated as

$$\sigma_{q_e}{}^2 = C^2 A^2 \int_{U/l}^{\infty} S(\tilde{n}) d\tilde{n} \qquad (5)$$

where $C = C_d \sqrt{C_p} / 2$.

The total root mean square (RMS) of the ventilation rate is

$$\sigma_q = \sqrt{\sigma_{q_e}{}^2 + \sigma_{q_p}{}^2} \qquad (6)$$

Note that the influence of temperature fluctuation is much smaller than the wind velocity fluctuation, thus the temperature fluctuation effect was not considered in this model. The model used Matlab™ to generate the real ventilation rate based on the mean and RMS of the ventilation rate that is calculated as above equations.

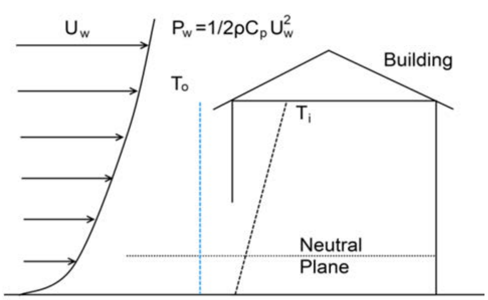


Figure 1 Pressure difference at the opening

The model was applied to simulate a one-zone small office building. The detail information of this simulation is listed in Table 1. The baseline building construction was based on ASHRAE Standard 90.1-2007 and there was no concrete in the exterior wall. Building2 was with 100 mm thickness of concrete in the exterior wall as thermal storage to improve night cooling performance. The hygroscopic process is neglected in the simulation since no active hygroscopic was used in the building construction. The total number of occupied hours (working hours) for the whole simulation period was 1377 hours. The simulations used the first order implicit method to solve energy equations for the indoor air and the building envelop with a time step of six minutes.

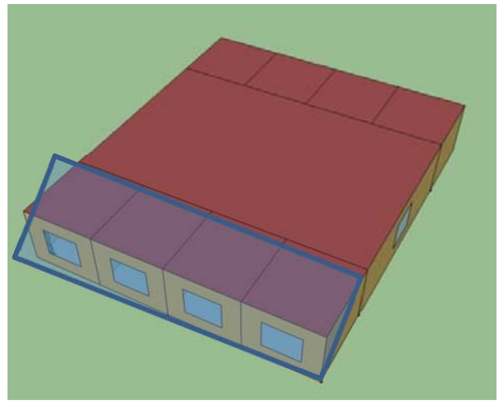
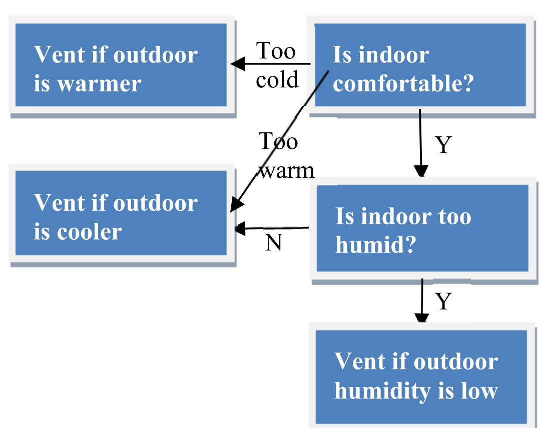
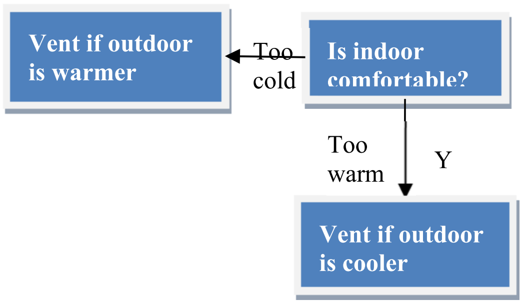


Figure 2 Building geometry

Figure 3 shows the three different control strategies. The first one (hereinafter "Control_1") as shown in Figure 3(a) controls both temperature and humidity. The first step is to decide whether indoor temperature is comfortable or not based on the adaptive model with 80% satisfaction rate. If the room temperature is not comfortable, natural ventilation will be used if outdoor temperature satisfies the condition. If the room temperature is comfortable, indoor humidity becomes a determining factor for ventilation. If indoor is humid and outdoor absolute humidity is lower than indoor one, natural ventilation will be used even though outdoor temperature is higher than indoor. Note that even though such occasion will increase the indoor air temperature, the prior condition to the humidity determination requires the indoor temperature to be comfortable. Therefore, the temperature increase will not cause the indoor temperature higher than the upper limit of the comfort zone for this time step.



(a)



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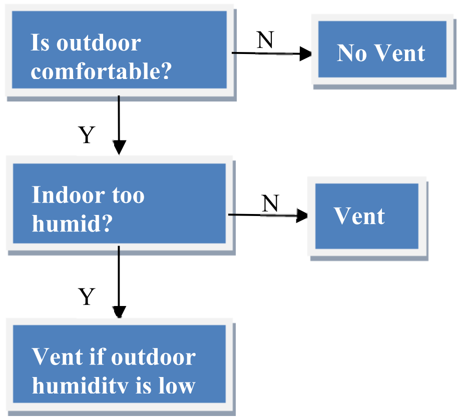

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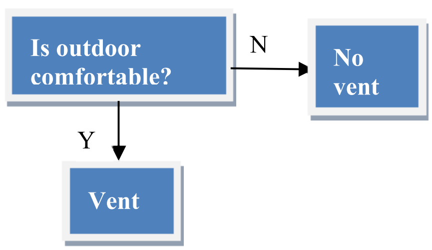

(d)

Figure 3 (a) Control both temperature and humidity (Control_1); (b) Control only temperature (Control_2); (c) Maximize ventilation hours with control on humidity (Control_3); (d) Maximize ventilation hours (Control_4)

The second control strategy (hereinafter "Control_2") as shown in Figure 3(b) is only based on indoor and outdoor temperature. The third control strategy (hereinafter "Control_3") as shown in Figure 3(c) tries to maximize the ventilation time while still maintain relatively good thermal comfort and low humidity level. The major difference between Control_3 and Control_1 is that Control_3 will use natural ventilation whenever the outdoor air temperature is within the comfortable range, even though outdoor air might be warmer than indoor. This will enable more ventilation time in exchange for sometimes an increase of indoor temperature. Control_3 can represent the case when the occupants want more fresh air for better IAQ. Figure 3(d) shows the control strategy (hereinafter Control_4) that tries to use natural ventilation whenever outdoor temperature is within thermal comfort zone, regardless of the humidity.

Note that all the control strategies are only used for the daytime when the office is occupied. The windows will remain open from 18:00 of the day to 07:00 of the next day to utilize night cooling.

RESULTS AND DISCUSSION

This study used adaptive thermal comfort model to evaluate natural ventilation performance. This model requires no mechanical system used during the whole period and people can freely control the window openings (Brager and Dear, 2001). Only based on these two prerequisites can we assume people will accept larger temperature swing than the PMV model. To satisfy those two requirements, this study did not use any mechanical system, which will results in some discomfortable hours and used control strategies that simulate human behaviors.

Table 2 summarizes the results for the four control strategies for the baseline building and building with more thermal mass. The "80%" and "90%" represents the number of occupied hours with 80% and 90% satisfaction rate, respectively. The "RH>80%" represents the number of occupied hours when the indoor relative humidity is higher than 80%. "VentTime" represents the number of occupied hours when natural ventilation was used. The results showed that passive cooling alone could satisfy cooling need for more than 80% of the time in Philadelphia based on temperature. However, the results show that a lot of time the indoor air was too humid without humidity control such as Control_2 and Control_4.

Figure 4(a) shows the percentage of number of occupied time when the indoor temperature meets the 80% satisfaction rate. Control_2 showed the best performance in terms of temperature control because it will utilize the most cooling potential from outdoor air. Control_1 has the least 80% satisfaction hours because when the indoor humidity is high, Control_1 will use the outdoor air to decrease the indoor relative humidity when outdoor absolute humidity is lower, even if the outdoor air is warmer. However, the indoor air cannot be heated up by outdoor air without bound. As shown in Figure 3(a), the first condition prior to humidity control is to ensure indoor temperature is within the comfort zone, and then the humidity control will determine whether to use outdoor air to reduce indoor relative humidity. Therefore, the decrease of the 80% satisfaction hours is less than the decrease of the high humidity hours for Control_1 compared with Control_2, as shown in Figure 4(b). Control_3 and Control_4 are the strategies that would maximize the ventilation time. Control_3 also controls the humidity while Control_4 only considers temperature. Their ventilation time is much longer than that with Control_1 and Control_2 as shown in Table 2. Their humidity level is between Control_1 and Control_2.

Figure 5 compares the performance of all control strategies for the baseline building. This study suggests that in addition to indoor temperature, humidity should also be a criterion for thermal comfort analysis in Philadelphia region. Based on both temperature and humidity, Figure 5 shows that Control_1 can provide the best overall thermal comfort for Philadelphia region.

As shown in Table 2 and Figure 4, adding more thermal mass will improve the sensible cooling process yet will result in higher relative humidity since passive cooling cannot remove latent heat. Table 1 shows that the increase of high humidity hours is similar to the increase of 80% satisfaction hours between baseline building and buliding2.

Generally, the natural ventilation time, indoor humidity and indoor temperature affect each other. Each control strategy has its own advantages and disadvantages and can represent different building owner's behavior. For instance, a person who cares more about IAQ and wants more outdoor air will use Control_3; a person who prefers relatively dry and cool indoor environment might use Control_1.

CONCLUSION

This paper investigated four human-behavior oriented control strategies for natural ventilation. The study used a small office building in Philadelphia region to evaluate the ventilation performance by simulating the thermal comfort in the building:

1) The control strategy that controls both the temperature and humidity provides the best overall thermal comfort for Philadelphia region;

2) The control strategies that maximizes the ventilation hours provide more ventilation time thus better IAQ among the four control strategies and have moderate performance in terms of thermal comfort;

3) Adding thermal mass into the building envelope will increase comfortable hours in terms of temperature but will also increase high humidity hours.

More on-site experiments will be performed in the near future to validate the control strategies and simulation results.

NOMENCLATURE

A = opening area
C_d = discharge coefficient
C_p = pressure coefficient
g = gravitational acceleration
h_1 = elevation of the lower edge of the window
h_2 = elevation of the upper edge of the window
l = width of the window
n = frequency
Q_{in} = incoming ventilation rate
Q_{out} = outgoing ventilation rate
S = velocity temporal spectrum
T_i = indoor air temperature
T_o = outdoor air temperature
$\bar{U}$ = window velocity at 10 m above ground
z_0 = neutral level elevation
z_{ref} = 10 m (reference level)
ΔP = pressure difference
σ_q = total RMS of ventilation rate
σ_{q_e} =RMS of ventilation due to eddy penetration
σ_{q_p} =RMS of ventilation due to pulsating flow
ρ_i = indoor air density
ρ_{out} = outdoor air density

REFERENCES

ASHRAE Inc., 2007. ASHRAE Standard 90.1.

ASHRAE Inc., 2010. ASHRAE Standard 55.

Brager, G. S., De Dear, R., 2001. Climate, Comfort, & Natural Ventilation: A New Adaptive Comfort Standard for ASHRAE Standard 55, Moving Thermal Comfort Standards into the 21st Century, Windsor, UK.

Hensen J. 2003. Paper Preparation Guide and Submission Instruction for Building Simulation 2003 Conference, Eindhoven, The Netherlands.

Menassa, C. C., Taylor, N., Nelson, J., 2013. A Framework for Automated Control and Commissioning of Hybrid Ventilation Systems in Complex Buildings, Automation in Construction, 30, 94-103.

Mitchell, J.W., Beckman, W.A. 1995. Instructions for IBPSA Manuscripts, SEL, University of Wisconsin, Madison USA.

Roetzela, A., Tsangrassoulisb A., Dietricha, U., Busching, S., 2010. A review of Occupant Control on Natural Ventilation, Renewable and Sustainable Energy Reviews 14(3), 1001-1013.

Spindler, H.C., Norford, L.K. 2009. Naturally Ventilated and Mixed-mode Buildings. Part II: Optimal Control, Building and Environment 44(4), 750-761.

Van Paassen, A.H.C., Liem, S.H., Groeninger , B.P., 1998. Control of Night Cooling with Natural Ventilation: Sensitivity Analysis of Control Strategies and Vent Openings, AIVC 19th

Conference, proceedings of "Ventilation Technologies in Urban Areas", Oslo, Norway.

Wang, H. and Chen, Q. "A new empirical model for predicting single-sided, wind-driven natural ventilation in buildings," Energy and Buildings, 54, 386-394.

Yun, G.Y., Steemers, K., Baker, N., 2008a. Natural Ventilation in Practice: Linking Façade Design, Thermal Performance, Occupant Perception and Control, Building Research & Information, 36 (6) 608–624.

Yun, G.Y., Steemers, K., Baker, N., 2008b. Time-Dependent Occupant Behaviour Models of Window Control in Summer, Building and Environment, 43, 1471–1482.

Table 1 Detailed information of simulation (Construction material based on ASHRAE Standard 90.1 (2007))

<table>
<tr><td>Run Period</td><td colspan="2">May 1st – Sept 30th</td></tr>
<tr><td>Weather Data</td><td colspan="2">TMY3 Philadelphia Airport</td></tr>
<tr><td>Building Geometry</td><td colspan="2">3.89 m × 14.26 m × 3.05 m</td></tr>
<tr><td rowspan="2">Exterior Wall
(From outside to inside)</td><td>Baseline building</td><td>Additional thermal mass</td></tr>
<tr><td>25mm Stucco/
R-0.74 Insulation/
12.7mm Gypsum</td><td>25mm Stucco/
R-0.74 Insulation/
100mm Concrete/
12.7mm Gypsum</td></tr>
<tr><td>Interior Wall</td><td colspan="2">19mm gypsum board/
R-0.15 Airspace resistance/
19mm gypsum board</td></tr>
<tr><td>Roof
(From outside to inside)</td><td colspan="2">0.9mm Roof membrane/
R-4.3 Insulation/
Metal decking</td></tr>
<tr><td>Floor</td><td colspan="2">100mm MAT-CC05 Concrete</td></tr>
<tr><td>Glazing</td><td colspan="2">4 windows: Each with area of 0.8 m x0.7 m
U=3.2; Solar Heat Gain Coefficient = 0.49</td></tr>
<tr><td>Internal Gain</td><td colspan="2">Working hours: 8:00-17:00
4 people: Sensible heat 75 W, latent heat 55 W per person
Electricity Equipment: 10.7 W/m^2
Lighting: 10 W/m^2</td></tr>
</table>

Table 2 Summary of Thermal Comfort for Different Control Schemes

<table>
<tr><th>UNIT: Hour</th><th>Total Hours</th><th>80%</th><th>90%</th><th>RH>80%</th><th>Vent Time</th></tr>
<tr><td colspan="6">Baseline BUILDING</td></tr>
<tr><td>Control_1</td><td rowspan="4">1377</td><td>1076</td><td>783.4</td><td>288.1</td><td>517.7</td></tr>
<tr><td>Control_2</td><td>1189.5</td><td>908.5</td><td>699.1</td><td>360.5</td></tr>
<tr><td>Control_3</td><td>1183.7</td><td>893.5</td><td>492.9</td><td>680.6</td></tr>
<tr><td>Control_4</td><td>1125.8</td><td>890.1</td><td>539.9</td><td>776</td></tr>
<tr><td colspan="6">With more thermal mass</td></tr>
<tr><td>Control_1</td><td rowspan="4">1377</td><td>1134</td><td>865.1</td><td>247</td><td>1042.4</td></tr>
<tr><td>Control_2</td><td>1232.3</td><td>1011.1</td><td>673.2</td><td>1531.3</td></tr>
<tr><td>Control_3</td><td>1232.2</td><td>1008.5</td><td>484.8</td><td>1319.7</td></tr>
<tr><td>Control_4</td><td>1171.2</td><td>995.5</td><td>536.7</td><td>1389.8</td></tr>
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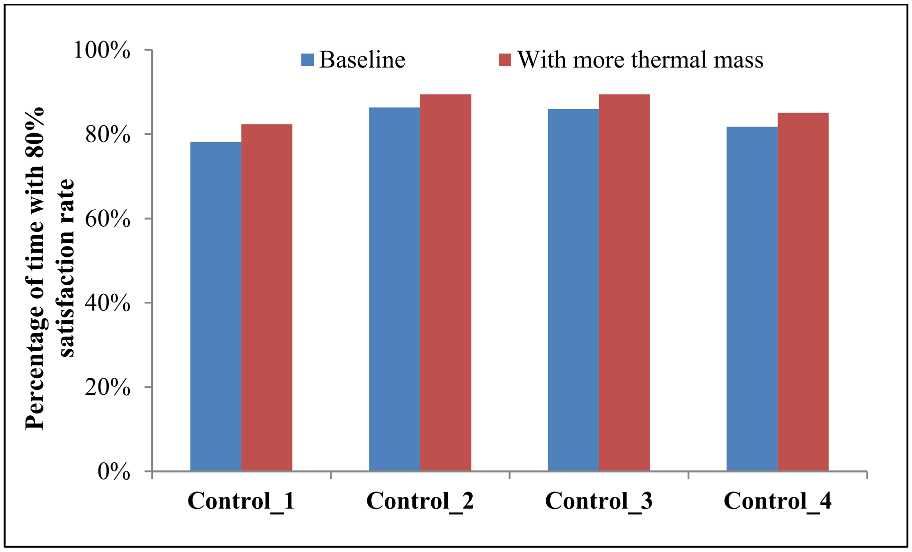
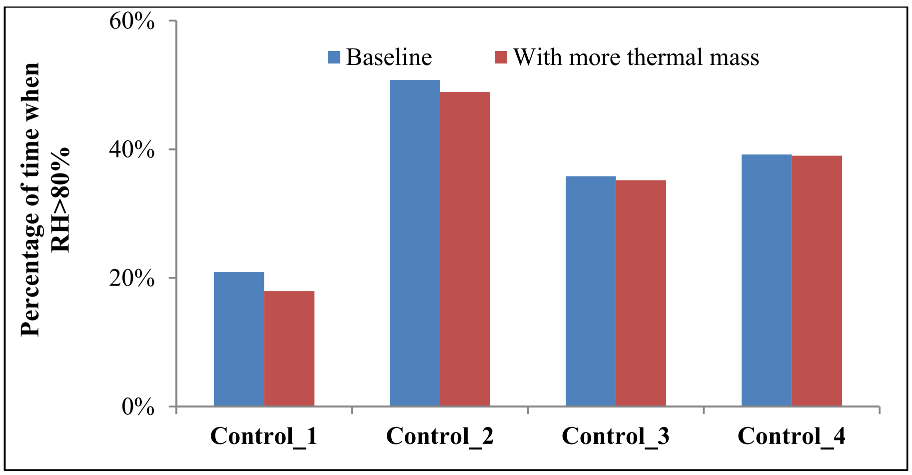


(a)



(b)

Figure 4 Percentage of total working time for different control strategies (a) with 80% satisfaction rate (b) when relative humidity is above 80%

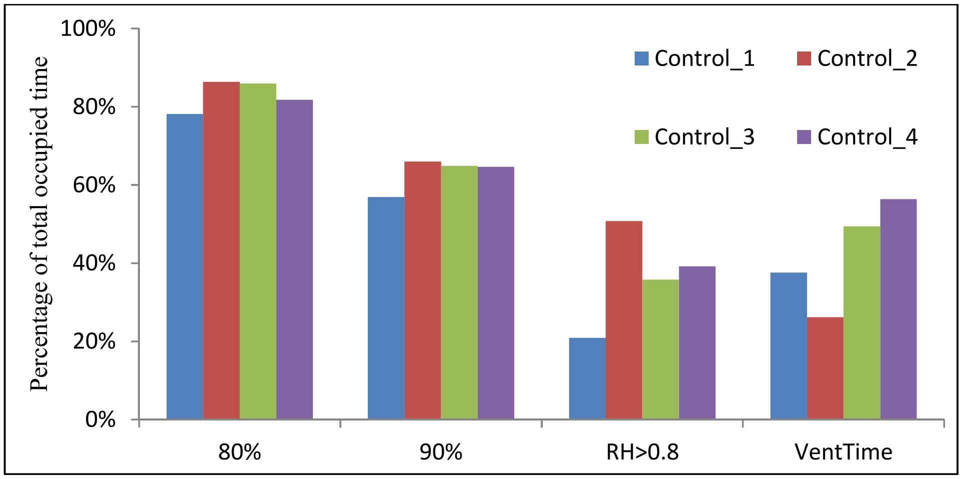


Figure 5 Performance of different control strategies