Optimal control for the natural ventilation in buildings with large depth

Fulin Wang1,*, Rui Yan1 and Yansheng Liu2
1 Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China
2 Beijing Mumaren Software Co. Ltd., Beijing 100068, China
* flwang@tsinghua.edu.cn

Abstract. This article proposes an optimal control method for the natural ventilation in buildings with large depth. Through designing control strategy, constructing building model, simulating the performance of natural ventilation under different control strategies, the optimal positions of the natural ventilation opening at different floors are decided to achieve the maximum free cooling and minimum cooling consumptions while ensuring the indoor air quality healthy. By using simulation, the cooling energy consumptions at three typical climate conditions, i.e. cool day, warm day, and moderate day, are simulated under two different control strategies, i.e. the proposed optimal control and traditional on/off control of natural ventilation opening. Based on the simulated energy consumptions at the three typical climate conditions, the annual total cooling energy consumptions are estimated. The annual total energy consumptions of optimal control can save cooling energy by 43.5% compared with the traditional on/off control, which shows the energy saving potential and the application prospective of the proposed optimal control method.

1. Introduction

Natural ventilation uses the natural forces of wind pressure or stacks effect to drive air to flow in/out a building. Natural ventilation is considered a beneficial measure to realize both energy efficient building and healthy indoor environment because it can achieve free cooling by inducing outdoor cool air but needs not consume any fan energy and chiller energy. Many researchers focus on studying the natural ventilation potential and performance [1]-[7]. Several researches study the method for simulating the performance of natural ventilation [8]-[10]. Energy saving potential of utilizing natural ventilation is studied as well [11]-[13]. Some researchers studied the active control for natural ventilation to achieve minimum energy use and balanced air flow rate for the rooms at different locations [14]-[15].

However, most researches on natural ventilation focuses on residential buildings. Furthermore, most natural ventilations are single side ventilation with passive mode without active control. Especial for the building with large depth, single side ventilation cannot drive outdoor air to the deep inside of rooms. For the purpose of let the outdoor air can reach the deep inside of rooms, ventilation shaft is often used to increase the natural ventilated air flow rate. If there is no control for the natural ventilation of the buildings with large depth and ventilation shaft, the rooms located on upper of the neutral plan, outdoor air cannot enter these rooms. For the purpose of let all room can have naturally ventilated outdoor air flow in, active control of window opening is needed. This paper focus on develop the methodology for optimal control of the window opening for buildings with large depth and ventilation shaft. A case study building located in Qinhuangdao city in China is analyzed using simulation to verify the natural ventilation performances and energy saving potentials of the proposed optimal control of window opening.
2. Methodology
The optimal control objectives include: 1) every room can have the outdoor air flow in; 2) The total outdoor air flow are as much as possible; 3) air temperature of every room locates in the comfort range of 18 to 27°C. To achieve such optimal control objectives, control strategies consisting of two steps are developed: 1) feedforward control of window openings are calculated with Equation 1 to 5; Equation 1 shows the total pressure formed by thermal and wind pressure; Equation 2 shows the thermal pressure at the height of \( H \); Equation 3 calculates the wind pressure given window orientation and wind speed; Equation 4 is used to calculate the air flow rate given flow coefficient \( C_Q \) and pressure; Equation 5 is used to calculate flow resistance given window opening; 2) feedback control of window opening by measuring the indoor air temperature to precisely control the window opening to let room air temperature locate in comfort range.

\[
P = P_t + P_w \tag{1}
\]

\[
P_t = (\rho_0 - \rho_i) g (H_{NPL} - H) \tag{2}
\]

\[
P_w = C_w \frac{\rho_0 V H^2}{2} \tag{3}
\]

\[
Q = C_Q P^{0.5} \tag{4}
\]

\[
C_Q = \sqrt{2 \rho_0 K A C_d} \tag{5}
\]

Where,
\( P \): Pressure that drives natural ventilation, Pa
\( P_t \): Thermal pressure caused by the temperature difference between indoor and outdoor air, Pa
\( P_w \): Wind pressure caused by the wind blowing to the window, Pa
\( \rho_0 \): Outdoor air density, kg/m³
\( \rho_i \): Indoor air density, kg/m³
\( g \): Acceleration of gravity, m/s²
\( H_{NPL} \): Height of neutral plan, m
\( H \): Height of room, m
\( C_w \): Wind pressure coefficient, which can be decided according to Figure 1
\( C_H \): Wind speed are height \( H \), m/s
\( Q \): Natural ventilation air flow rate, m³/s
\( C_Q \): Air flow coefficient, m³/sPa⁻⁰·⁵
\( K \): Window opening percentage
\( A \): Window area, m²
\( C_d \): Air flow coefficient per unit area, m³/skg, \( C_d = 1.244 \)

Figure 1. Wind pressure coefficients corresponding to wind angle [16].

The simulation model of a case study building located in Qinhuangdao city in China is built using Matlab Simulink to simulate the natural ventilation performances and energy saving potentials when the windows are controlled by the proposed optimal control strategy. The simulation model built in Simulink is shown in Figure 2.
3. Results

The annual hourly outdoor air temperatures where the case study building located are shown in Figure 3. During the climate data, three typical days representing cool day, moderate day and warm day are picked out for detailed simulation study. The outdoor air temperatures of the three typical days are shown in Figure 4.

Take the cool day simulation result as an example, the windows opening of the room at four different floors, room air temperatures, natural ventilated air flow rate, and the energy consumptions of proposed optimal control and the traditional on/off control are shown in Figure 5.
(a) Window opening of the rooms at four different floors

(b) Indoor air temperature of the rooms at four different floors.

(c) Natural ventilation air flow rate of the rooms at four different floors.

(d) Energy consumption of the air-conditioning system with proposed optimal control
If extend the three typical days’ energy consumption results to the whole cooling season by simply multiplying the days similar to the three typical days, the annual air-conditioning energy consumption can be obtained. During the whole cooling season, where are 66 cool days, 38 moderate days, and 55 warm days. The daily air-conditioning energy consumptions are 0, 13.9 and 144.4 kWh corresponding to cool day, moderate day and warm day respectively, when the proposed optimal control implemented. Compared with the proposed optimal control, the daily air-conditioning energy consumptions are 22.2, 138.9 and 150 kWh corresponding to cool day, moderate day and warm day respectively, when implementing traditional on/off control. The annual energy saving rate are 43.5%. The energy consumption comparison is shown in Table 1.

**Table 1. Annual air-conditioning energy consumptions.**

|                      | Cool day | Moderate day | Warm day |
|----------------------|----------|--------------|----------|
| The proposed control (kWh) | 0.0      | 13.9         | 144.4    |
| Traditional on/off control (kWh) | 22.2     | 138.9        | 150.0    |
| Daily energy saving (kWh)       | 22.2     | 125.0        | 5.6      |
| Similar days of the typical day | 66       | 38           | 55       |
| Day percentage of natural ventilation |          |              | 43.6%    |
| Annual total energy saving by natural ventilation (kWh) |          |              | 6522.2   |
| Energy saving ratio by natural ventilation (kWh) |          |              | 43.5%    |

4. Discussion
The former described simulation results show the feasibility and energy saving potential of the proposed natural ventilation control system. For field application, the control can be achieved by the feed forward control logic shown in Equation 1 to 5, and the feedback control logic to fine tune the openings of windows. Each room is equipped with a control, room temperature sensor, and window opening actuator. The feed forward and feedback control logics are embedded in the controller.

5. Conclusions
This article proposes an optimal control method for the natural ventilation in buildings with large depth and ventilation shaft. The optimal control method aims to control the window opening to achieve: 1) every room can have the outdoor air flow in; 2) The total outdoor air flow are as much as
possible; 3) air temperature of every room locates in the comfort range of 18 to 27°C. Simulation model of a case study building was built in Matlab Simulink environment and the energy performance of the proposed optimal control and traditional on/off control are simulated and compared. The cooling energy consumptions at three typical climate conditions, i.e. cool day, warm day, and moderate day, are simulated corresponding to the proposed optimal control and traditional on/off control. The annual total cooling energy consumptions are estimated based on the simulated energy consumptions at the three typical days. The annual total energy consumptions of optimal control can save cooling energy by 43.5% compared with the traditional on/off control, which shows the energy saving potential and the application prospective of the proposed optimal control method.

Acknowledgement
This research is supported by National Key R&D Program of China, Research and Demonstration of Key Technology of Net-Zero Energy Building (Project Number 2016YFE002030) and Innovative Research Groups of the National Natural Science Foundation of China (Grant number 51521005).

References
[1] Chen Q 2009 Ventilation performance prediction for buildings: a method overview and recent applications Build. Environ. 44 (4) pp 848–858
[2] Etheridge D W 2012 Natural Ventilation of Buildings: Theory, Measurement and Design John Wiley & Sons, Chichester, UK
[3] Linden P F, Lane-Serff G F and Smeed DA 1990 Emptying filling boxes: the fluid mechanics of natural ventilation J. Fluid Mech 212 pp 309–335
[4] Li Y 2000. Buoyancy-driven natural ventilation in a thermally stratified one-zone building Build. Environ. 35 pp 207–214
[5] Li Y Li X F 2015 Natural ventilation potential of high-rise residential buildings in northern China using coupling thermal and airflow simulations Build. Simu. 8(1) pp 51-64
[6] Montazeri H, Montazeri F, Azizian R and Mostafavi S 2010 Two-sided wind catcher performance evaluation using experimental, numerical and analytical modelling Renew. Energy 35 pp 1424–1435
[7] Moosavi L, Mahyuddin N and Ghafar N A 2014 Thermal performance of atria: an overview of natural ventilation effective designs, Renew Sustain. Energy Rev.34 pp 654–670
[8] Oropeza-Pereza I, Østergaardb P A and Remmenb A 2012 Model of natural ventilation by using a coupled thermal-airflow simulation program Energy and Build. 49 pp 388–393
[9] Johnson M, Zhai Z and Krarti M 2012 Performance evaluation of network airflow models for natural ventilation HVAC&R Research 18(3) pp 349–365
[10] Bastide A, Lauret P, Garde F and Boyer H 2006 Building energy efficiency and thermal comfort in tropical climates. Presentation of a numerical approach for predicting the percentage of well-ventilated living spaces in buildings using natural ventilation Energy and Build. 38 pp 1093–1103
[11] Huang H 2013 Research on Evaluation Method of Natural Ventilation Performance of Northern High-rise Residential Buildings Master Thesis Tsinghua University
[12] Huang H, Li X F, Zhang M R and Li C 2012 Simulation Study on Annual Energy Consumption of Naturally Ventilated Buildings Building Science 28(2) pp 46-50
[13] Oropeza-Pereza I and Østergaardb P A 2014 Energy saving potential of utilizing natural ventilation under warm conditions – A case study of Mexico Applied Energy 130 pp 20–32
[14] Dong Y and Li P 2015 Natural ventilation of lower-level floors assisted by the mechanical ventilation of upper-level floors via a stack Energy and Build. 92 pp 296–305
[15] Turner W J N and Walker I S 2013 Using a ventilation controller to optimise residential passive ventilation for energy and indoor air quality Build. and Environ. 70 pp 20-30
[16] ASHRAE 2009 Airflow Around Buildings ASHRAE Handbook - Fundamentals (SI Edition), Chapter 24