MULTI-FACTOR OPTIMIZATION OF ENERGY PERFORMANCE IN NATURALLY VENTILATED BUILDING: A CASE STUDY OF OFFICE BUILDING IN HOT SUMMER AND COLD WINTER CLIMATE

Cong Li[1], *Youming Chen*[1*], *Quan Zou*[1]

[1]Hunan University, Civil Engineering Department, 410082, China

Abstract. Nowadays, building energy consumption is responsible for 30% to 40% of total energy usage in many countries. The energy performance of each building is related to many factors. Most of them are determined in design stage. Meanwhile, natural ventilation is one of the most potential passive energy conservation, especially in hot summer and cold winter climate zone. This study aims to figure out how to make the most of natural ventilation in building energy conservation in hot summer and cold winter climate zone. By comparing different building design plans, this study try to provide a method to help find the best-optimized building parameters design solutions. Six main factors are selected, including: building orientation, exterior wall masonry, window wall ratio, shading overhang depth, binds slat angel(include the situation when there is no blinds at all), exterior window structure. A seven-layer office building in hot summer and cold winter zone is modelled and simulated in Energyplus. Two building running plans are compared: (a) the air conditioning system is always on during office occupancy time; (b) the air conditioning system is off when natural ventilation can guarantee thermal comfort inside the building. The results shows, plan (b) saves more than 40% energy on different building parameters designs comparing to plan (a).

1 Introduction

Hot summer and cold winter zone is one of the most important climate zone in China where more than half of the population live. Hot summer and cold winter zone has a very good energy-saving potential of natural ventilation due to the potential of having a long free running period [1]. During the free-running naturally conditioned period, people choose to adjust the dressing isolation, ventilation opening status over to active the air conditioning system. Except helping with indoor thermal comfort, natural ventilation can also increase the rate of air flow, lower the average air age and improve the indoor air quality. The potential of natural ventilation is related to climate, urban topography, building geometry and thermal characteristics on the condition of thermal comfort. Some Chinese scholars conducted investigations and experiments on the adaptive thermal comfort of indoor occupants in various regions [2-4], and established adaptive thermal comfort models for various climatic zones including hot summer and cold winter zone. It provides a thermal comfort basis for the thermal performance design of indoor environment in hot summer and cold winter zone. Tong, et al. used the adaptive thermal comfort model and natural ventilation hours to evaluate natural ventilation potential of multi-stories buildings located in different climate zones all over the world [5, 6]. L. Yang and R. Yao, et al used PASCA hours and thermal resistance ventilation (TRV) models to estimate and evaluate the natural ventilation potential of buildings in various climatic regions in China [7, 8]. R. Yao did a case study on effect of several passive measures on thermal comfort and energy conservation in hot summer and cold winter climate in Yangtze River region[9]. It is indicated that the integration method of numerical calculation and building energy consumption simulation software is a good way to optimize the thermal performance based design of building natural ventilation[10].

2 Methods

The whole case study has three steps. Firstly, the geometric model of an office building was built in sketchup and more specific parameters were set in energyplus. Then six main factors were selected as the variables. 2000 independent cases of whole year energy consumption of this office building with different combinations of the variables were simulated in energyplus. The final step, the results were analyzed with support vector regression model. And best optimized design solutions can be found further on by using particle swarm optimization.

* Corresponding author: ymchen@hnu.edu.cn

2.1 Modeling

This case study is based on a seven-floor office building located in Changsha. Changsha(E 112°58', N 28°11') is located The building model was firstly built in sketchup, as shown in fig.1

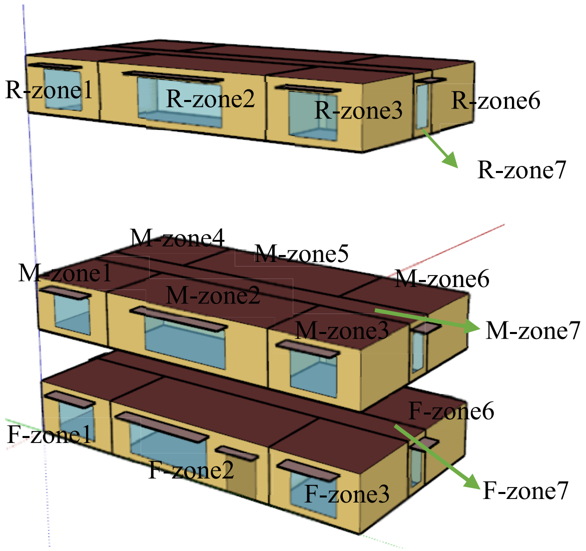

Fig. 1. The seven-floor office building

Each layer has six rooms connected by one corridor. To simplify it, every room has one window, the corridor has two small windows on both ends. Height of each floor is 3m. The four rooms on the corners are size 6m×5m×3m, width of the windows is 3m. The other two rooms in the middle are size 12m×5m×3m, width of the windows is 6m. In this building, except first floor and top floor, the other five floors have repetitive structures. The zonegroup object was used to reduce the amount of input necessary parameters in Energyplus.

2.2 Variables and thermal comfort methods

Six main factors are selected to be variables, including: building orientation, exterior wall masonry, window wall ratio, shading overhang depth, binds slat angle (include the situation when there is no blinds at all), exterior window structure. This case study includes 2000 independent simulations to collect enough data. In every independent simulation, value of each factors must be determined first, the explanations are as below:

(1) Building orientation: Since this building is nearly symmetrical, meaningful orientation range is from 0 to 90 degrees, at 15-degree intervals. 0 degree represents when the building entrance facing due south as in fig.1; other degrees represent when the building has rotated degrees clockwise from entrance facing due south.

(2) Exterior wall masonry: Three typical masonry structures were selected. Ordering by thermal resistance value, the three masonry structures are solid brick (thickness 0.24m, conductivity 0.81W/m·K), shale hollow brick (thickness 0.24m, conductivity 0.58W/m·K), aerated concrete (thickness 0.1m, conductivity 0.18W/m·K). All exterior walls has EPS insolation layer. To keep the heat transfer coefficient of whole exterior wall smaller than 0.80W/(m2·K)[], the thickness of isolation layer was calculated.

(3) Window wall ratio (wwr): To make it convenient to adjust the wwr during simulations, in this case study the windows' width is invariant. The wwr adjustment is accomplished by changing the height of the windows. All windows have the same height and change at the same time. The range of window height is from 0.9m to 2.2m, which leads the wwr to range of 10% to 30.55%, at 0.1m intervals.

(4) Shading overhang depth: The range of shading overhang depth is from 0.6m to 1.5m.

(5) Interior blinds slat angle: The range of interior blinds slat angle is from 15 to 90 degrees, at 15-degree intervals. The situation that there is no interior blinds at all was also considered. A value as 100 is used to represent this situation.

(6) Exterior window structures: Four typical window structures are selected: clear glass 6mm+air 12mm+clear glass 6mm, clear glass 6mm+argon gas 12mm+clear glass 6mm, Low-e clear glass 3mm+air 12mm+clear glass 6mm, Low-e clear glass 3mm+argon gas 12mm+ clear glass 6mm.

Every independent simulation case randomly select the values of the six variables given above. All other parameters of the building stay the same all the time. The object value is annual total energy consumption of the seven-floor office building.

Changsha has a typical hot summer and cold winter climate, temperature range is from -5℃ to 38℃. Between the very uncomfortable hot summer days and cold winter days, there are many hours that the natural ventilation is enough to create an acceptable indoor thermal environment. Every independent case was simulated following two plans. (a) The air conditioning system is off when natural ventilation can guarantee thermal comfort inside the building. (b) The air conditioning system is always on during office occupancy time. This is a very energy wasting plan, however truly exists.

In plan (a), to figure out when the air conditioning system is needed, the building was simulated for whole year without air conditioning system. According to the results from this free-running simulation, a schedule of air conditioning was made. The key is to judge if the room's temperature and humidity meet 80 of the occupants' thermal comfort requirements. Three thermal comfort methods were used in this study.

Since all rooms can be occupant-controlled naturally conditioned, the adaptive model given in ASHRAE Standard 55-2020 can be used when prevailing mean outdoor temperature is greater than 10℃ and less than 33.5℃. The equations are given as below:

$$\textit{Upper 80\% acceptability limit } (°C) = 0.31 + 21.3 \quad (1)$$
$$\textit{Lower 80\% acceptability limit } (°C) = 0.31 + 14.3 \quad (2)$$

Additionally, when average air speed is greater than 0.3m/s, the upper acceptability limit can be lower:

Table 1. Increases in acceptable operative temperature limits in occupant-controlled naturally conditioned spaces resulting from increasing air speed above 0.3m/s.

Average Air Speed 0.6 m/s	Average Air Speed 0.9 m/s	Average Air Speed 1.2 m/s
1.2°C	1.2°C	1.2°C

Clearly there are some time of the year that the mean outdoor temperature is beyond this range. The standard indicates that the prevailing mean outdoor temperature should be based on no fewer than 7 days and no more than 30 sequential days. Since this is an office building, the occupants follow the schedule of working from Monday to Friday in a week. And it's suggested that 6 warmup days is generally enough on the minimum end of the spectrum to avoid false predictions of convergence and thus to produce enough temperature and flux history to start EnergyPlus simulation. Every independent simulation case was simulated week by week. The whole year was divided into 13 periods, every period includes 4 weeks. The prevailing mean outdoor temperature is based on mean outdoor temperature of last period to the calculated period. From the typical meteorological year weather file, the fifth to thirteenth periods (April 23th to December 31th) has prevailing mean outdoor temperature less than 10℃.

For the first to fourth periods (January 1st to April 23th), analytical comfort zone method and elevated air speed comfort zone method were used. The codes in ASHRAE Standard 55-2020 Normative Appendix B and D were recoded in python language.

2.3 Optimization

After 2000 independent cases were simulated, support vectors regression method was used to receive a fit model that can be used to predict energy consumption of any combination of the variables. At last, the fit model was introduced as the objective function into particle swarm optimization method. Duel to the size limitation of this paper, please check online about more specific information about support vectors regression and particle swarm optimization methods.

3 Results and discussion

There are 2000 independent cases simulated. 80 percent of the cases were used as the training data, the rest were used as the test data. Support vectors regression method was introduced from scikit-learn library. The Gaussian radial basis function was used as the kernel function[11]. Using the score function based on R2 given by scikit-learn, the fitted model got a score of 0.95 (1 is best, 0 is poorest). This fitted model meets expectation, it can be used as the objective function in particle swarm optimization method.

Among all the six variables, Exterior wall masonry and exterior window structure are strictly discrete values. Exterior wall masonry has 3 different values and exterior window structure has 4 different values. The best thermal performance variables combination should be searched in 12 four-dimension spaces. Using particle swarm optimization method introduced from scikit-opt library, the best thermal performance variables combination is:

Orientation: 29 degrees (building clockwise rotated from entrance facing due south)

Exterior wall masonry: solid brick (thickness 0.24m, conductivity 0.81W/m·K)

Window wall ratio: 11% (window height is 0.9m)

Shading overhang depth: 1.1m

Interior blinds slat angle: 38 degree

Exterior window structures: clear glass 6mm+air 12mm+clear glass 6mm

With this variables combination, the annual energy consumption of plan (a) is predicted to be 869GJ by support vector regression. Meanwhile using this variable combination to simulate in Energyplus, the annual energy consumption is 875GJ. The relative error is as small as 0.69%, which is acceptable. The energy consumption of full occupant time air conditioned as plan (b) is 1232GJ. Except the air conditioning system, the building has a basic energy consumption including lighting, computers, printers and other necessary electrical equipment. The annual basic energy consumption of this building is 402GJ. Therefore, by making the most of natural ventilation, the thermal comfort energy consumption was saved by 43%.

Noticing that in this combination, the window height is 0.9, which is the lower limit of window height in this study. It indicates that window wall ratio is the most important key factor of annual energy consumption. Furth study will be processed.

References

1. B. Li, C. Du, R. Yao, W. Yu, V. Costanzo, Applied Thermal Engineering **129**, 693 (2018)
2. Y. Zhu, Q. Ouyang, B. Cao, X. Zhou, J. Yu, Indoor Air **26**, 125 (2016)
3. H. Yan, Y. Mao, L. Yang, Energy and Buildings **141**, 28 (2017)
4. H. Liu, Y. Wu, B. Li, Y. Cheng, R. Yao, Energy and Buildings **140**, 9 (2017)
5. Z. Tong, Y. Chen, A. Malkawi, Applied Energy **193**, 276 (2017)
6. Y. Chen, Z. Tong, A. Malkawi, Building and Environment **122**, 386 (2017)
7. L. Yang, G. Zhang, Y. Li, Y. Chen, Building and Environment **40**, 738 (2005)
8. R. Yao, B. Li, K. Steemers, A. Short, Renewable Energy **34**, 2697 (2009)
9. R.Yao, V. Costanzo, X. Li, Q. Zhang, B. Li, Journal of Building Engineering **15**, 298 (2018)
10. S. Omrani, V. Garcia-Hansen, B. Capra, R. Drogemuller, Building and Environment **116**, 182 (2017)
11. X. Li, R. Yao, Energy **212**, 118676 (2020)