Study on joint management of indoor natural ventilation environment by coupling ceiling fan with air conditioner

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1. Introduction

The world is now severely challenged by energy and environmental issues. As countries realize the vision of building a strong country and delivering a better life, the world’s energy demand will be increasing vigorously, and energy competition will be more intense in the future. Therefore, China urgently needs to reduce energy consumption and adjust the energy supply structure to improve energy strategic security. Building energy consumption accounts for one-third of the total energy demand in China. More than 60% of the building energy consumption is used to create a comfortable thermal environment. Therefore, how to create a comfortable, energy-efficient and environmentally friendly living environment will be directly related to the success of our country to cope with the challenges arising from energy and environmental issues.

It is well known that natural ventilation is regarded as one of the most promising passive strategies to reduce building energy consumption and improve indoor air quality and thermal comfort. Most studies of natural ventilation focus on the influence of ventilation performance (Omrani et al. 2017; Wang et al. 2014; Polak et al. 2019; Li and Chen 2020), thermal comfort environment (Tablada et al. 2009; Lu et al. 2015; Tian et al. 2020), assessment criteria (Wang and Malkawi 2019; Meng et al. 2016; Yoon et al. 2020), energy-saving performance (Mukhtar, Yusoff, and Ng 2019; Piselli et al. 2020) etc. In the past decade, there has been a lot of research on the energy saving and efficiency of natural ventilation. Homod et al. (Homod, Sahari, and Almurib 2014) used MGFC to predict the rate of change of indoor air potential energy storage and proposed that strategy could save up to 31.6% of energy consumption in the residential houses to achieve thermal comfort. Park and Lee (2020) developed a ventilation strategy that was characterized by high energy-saving and ventilation efficiency and analyzed the reduction of ventilation and cooling load reductions by opening and closing windows. The results showed that the improved natural ventilation strategy could effectively establish the required indoor conditions. Xu et al. (2016) studied the optimal joint control of heating, ventilation, and air conditioning systems and natural ventilation in a meeting room at the start-up stage. The theoretical analysis indicated that the optimal control policy of heating, ventilation and air conditioning can be well approximated by the threshold policies after natural ventilation is applied; the optimal control policy of natural ventilation can be greatly approximated by the threshold policy, when the indoor air temperature as a function of time has monotonicity after the heating, ventilation and air conditioning policy is applied. In addition, they establish a rule-based legal framework with policy approximation for joint control of heating,
ventilation, and air conditioning and natural ventilation. It is worth noting that there are few studies on the interaction between air conditioning and electric fans in naturally ventilated rooms.

Technologies used to create a comfortable environment mainly include air conditioner, electric fan etc. (Takasu et al. 2017; Jia and Sun 2018; Luo et al. 2015; Roghanchi, Kocsis, and Sunkpal 2017; Yang et al. 2015; Schiavon et al. 2017). At present, the air conditioner is mainly based on vapor compression refrigeration, and it requires extremely high energy consumption and economic costs despite its fantastic refrigeration performance. The electric fan generates a wind belt through the air flow, giving a cool feeling to residents living inside, but it does not change surrounding temperature and humidity. Although electric fans are more economical, they do not help a person stay cool when the indoor temperature is overwhelmingly higher than body surface temperature (Jia and Sun 2018). The combination of air conditioner and electric fan can achieve the purpose of comfort and energy saving under the condition of excellent air distribution. Air distribution plays an important role in the thermal comfort and energy utilization of air-conditioned rooms. Optimizing the air distribution mode of air-conditioned rooms will undoubtedly further improve the energy saving of the HVAC system.

In recent years, more and more researches have been made on the thermal comfort of air-conditioned rooms (Chen et al. 2018; Putra 2017; He et al. 2016; Lin et al. 2005; Sekhar and Ching 2002). In the study of Lin et al. (2005), a validated computational fluid dynamics model was used for numerical simulation to study and compare the performance of displacement and mixed ventilation under different boundary conditions. However, these studies do not pay much attention to the interaction between air conditioners and electric fans in naturally ventilated rooms. The probability of using air conditioning in naturally ventilated rooms is often deliberately ignored by people because they believe that unstructured natural ventilation will increase the energy consumption of air conditioners. In fact, in hot summer, an individual may have to work in a naturally ventilated environment, in which an air conditioner or electric fan is essential. Therefore, it is of practical significance to study the joint management of indoor natural environment coupled with an electric fan and air conditioner. In this paper, the indoor thermal environment of a studio with high personnel density, large fresh air load, large enclosure structure load and large indoor heat dissipation were studied. The air distribution models of the studio with ventilation openings under three treatment modes, namely fans, air conditioners and fans coupled with air conditioners were respectively numerically simulated to reveal the relationship between air distribution and human thermal comfort in each scheme. Finally, the optimal air distribution scheme was proposed based on energy saving and comfort under three modes.

2. Research objective and scheme

2.1. Research object

In order to figure out the interaction between air conditioning and electric fans in naturally ventilated rooms, the studio with ventilation openings shown in Figure 1, which was temporarily reconstructed from an ordinary classroom, was selected as the research object. The studio was on the top floor of an academic building in the hot-summer and cold-winter area. The net internal dimensions of the studio were measured as 7.6 m × 3.2 m × 3 m, and the studio consisted of two outer walls facing to the south and west and a wall facing to north and adjacent to a ventilation corridor. The adjacent rooms on the east side of the studio were not air-conditioned. Figure 1 shows the floor plan of the studio. Six fluorescent lamps were mounted on the ceiling, and six staff members sit at their desks and work on computers all year round. To ensure plenty of fresh air in the studio, ventilation openings were installed on the north and south walls of the studio. The typical characteristics of the studio were high personnel density, large fresh air load, large enclosure structure load and high indoor heat dissipation. The working conditions in the studio could be very harsh in summer and indoor temperature could be very high. Chamber tests with human subjects have proved that

![Figure 1. Studio floor plan.](image-url)
when the outdoor dry-bulb temperature was 28°C, the indoor sensible temperature was as high as 35°C. It is a difficult task for the staff to work efficiently in such a harsh environment, so it is essential to add effective air conditioning equipment in the studio to make the working environment more comfortable.

2.2. Experimental scheme and design ideas
The research object was the studio with ventilation openings shown in Figure 1. Its typical characteristics were the high density of personnel, large fresh air load, large enclosure structure load and high indoor heat dissipation. The working condition of the studio is intensely terrible in summer, so it is necessary to take proactive measures to improve the working conditions of staff. This paper is intended to obtain an energy-saving and comfortable scheme suitable for an indoor environment with high heat dissipation and personnel density by applying dual or multi-coupling environmental treatment measures. The air treatment scheme for the studio is shown in Table 1. In the table, Scheme

| No. | Measures                                | Location                  | Layout diagram |
|-----|----------------------------------------|---------------------------|----------------|
| 1   | Fans and vents coupled                 | Fans evenly arranged on the ceiling |                |
| 2   | Air conditioners and vents coupled     | Air-conditioning east wall layout |                |
| 3   |                                        | Air-conditioning west wall layout |                |
| 4   |                                        | Air-conditioning south wall layout |                |
| 5   | Air conditioner fans and vents coupled | Air-conditioning east wall layout |                |
| 6   |                                        | Air-conditioning west wall layout |                |
| 7   |                                        | Air-conditioning south wall layout |                |
1 is the mixed ventilation mode of natural vent and ceiling fan; Scheme 2–4 is natural ventilation coupled by air conditioning; Schemes 5 and 6 are the triple coupling mode of natural ventilation, air conditioning and ceiling fan. In Schemes 1, 5–7, two ceiling fans are hung uniformly from the ceiling of the room. In Schemes 2–7, air conditioner was installed in the middle of the wall, except the north wall which was 2.4 m above the ground. The reason why the air conditioner was not installed on the north wall was that the surface temperature of the north wall was lower than that of the south wall due to hot pressing, and that the ventilation effect of the northern exhaust outlet was stronger than that of the southern one. Thus, the air conditioner installed on the north wall would reduce natural ventilation capacity, thus requiring more air supply energy.

2.3. Assessment parameters of indoor environmental

Thermal comfort evaluation is the basis of the study, and indoor air quality should also be taken into account.

2.3.1. PMV – PPD indices

The Predicted Mean Vote index (PMV) is the most commonly used index for thermal evaluation in recent years. The PMV indicates the feeling of the vast majority of individuals about the same environment. The seven-level physiological and psychological thermal sensation scale shown in Table 2 was used for the PMV index, as the American Society of Heating, Refrigerating and Air-Conditioning Engineer (ASHRAE) thermal sensation scale does. The dissatisfaction percentage of the thermal environment is used as the Predicted Percent Dissatisfied index (PPD).

International Standardization Organization (ISO), ASHRAE and other organizations have relevant regulations on the comfort standard of indoor thermal environment that PMV index shall be between plus or minus 0.5 and that PPD index be less than 10%. Many scholars believe that these standards are too high, difficult to achieve or even unnecessary in most areas of China. Generally speaking, the acceptable PMV index acceptable for a thermal environment is: −1.0< PMV<1.0, correspondingly PPD<27% (Pan et al. 2005).

2.3.2. Air age

Air age reflects the exchange efficiency of indoor air (Bojic, Yik, and Lo 2002). Air age is an important index to evaluate indoor ventilation effect and indoor air quality. As the air enters the room from the air inlet, pollutants are constantly mixed in. Obviously, air age is an index to evaluate the rationality of the airflow state.

3. Mathematical and physical models

The object of this study can be simplified as the studio model shown in Figure 2. The conditions of the studio are described in Chapter 2.1. The studio has two ventilation openings, a 0.4 m × 0.6 m vent on the south wall and a 0.8 m × 0.3 m window above the north entrance. In order to obtain a unified experimental analysis

| Table 2. PMV physiological and psychological thermal sensation scales. |
|---------------------------------------------------------------|
| Thermal sensation | Cold | Cool | Slightly cool | Comfort | Slightly warm | Warm | Hot |
| PMV scale          | 0–3  | 0–2  | 0–1           | 0       | 0–1           | 0–2  | 0–3 |

Figure 2. Studio model.
Table 3. Heat sources that may be involved in schemes.

| Items                  | Quantity | Specifications | Conditions                  | Performance parameter |
|------------------------|----------|----------------|-----------------------------|-----------------------|
| Building envelope      |          |                | Constant temperature       | 30°C                  |
| Fluorescent Lamp       | 6        | 1.2 m length   | Constant heat flow          | 40 w                  |
| Person                 | 6        | Sitting, clothing thermal resistance is 0.37 clo. | Constant heat flow     | 60 w                  |
| Laptop computer        | 6        |                | Constant heat flow          | 90 w                  |
| Ceiling fan            | 2        | Air volume is 190 m2/min, rotate speed is 370 r/min. |                |                      |
| Air-conditioned indoor unit (wall-mounted) | 1 | Boundary dimension is 0.95 m x 0.3 m x 0.2 m | Constant heat flow opening | 100 w |
| Air supply vent of the air conditioner | 1 | 0.1 m x 0.95 m |                |                      |
| Return vent of the air conditioner | 1 | 0.2 m x 0.95 m |                |                      |
| Ventilation opening 1  | 1        | 0.4 m x 0.6 m  | opening                     | Pressure openings      |
| Ventilation opening 2  | 1        | 0.8 m x 0.3 m  | opening                     | Pressure openings      |

In order to simplify the problem, the following assumptions are made:

1. The air in the studio was incompressible and met Bossinesq assumptions; (2) The air flow in the room was steady-state turbulence;
2. The air flow in the room was steady-state turbulence;
3. Indoor air was a radiating transparent medium.

3.1. Governing equations

(1) Continuity equation:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]  

(1) where \( u_i \) is the velocity in the \( i \) direction.

(1) Momentum equation

\[
\frac{\partial}{\partial x_j} \left( \rho u_i u_j \right) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \tau_{ij} \right) + \rho g_i + F_i
\]

(2) where \( \rho \) is the fluid density; \( p \) is static pressure; \( \tau_{ij} \) is the viscous force tensor; \( g_i \) is the volume force in the \( i \) direction; \( F_i \) is the source term caused by a heat source, pollution source, etc.

\[
\tau_{ij} = \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right)
\]

(3) Figure 3. Air velocity profile in the lengthwise section \( X = 0 \) m of Scheme 1. (a) Iso-temperature line. (b) The velocity fields.
Where $\mu$ is the dynamic viscosity, and the second term on the right as in Equation (3) is the effect of volume diffusion.

(1) Energy conservation equation

$$\frac{\partial}{\partial x_i} (pu_i h) = \frac{\partial}{\partial x_i} (k + k_t) \frac{\partial T}{\partial x_i} + S_h$$

(4)

where $k$ is molecular thermal conductivity; $k_t$ is the heat conductivity caused by turbulent diffusion, $k_t = c_p \mu T / Pr_t; S_h$ is the volume heat source.

3.2. Boundary conditions

Constant heat flow boundary condition was used for indoor heat source, velocity boundary condition for air supply outlet, free boundary condition for air return inlet and outlet, and constant temperature boundary condition for wall surface in Airpak. The specific boundary conditions for the simulation involved in each test scheme are shown in Table 3.

4. Simulation and analysis

This paper focuses on the discussion of the design method and strategy of multi-dimensional ventilation environment based on energy saving and comfort. The studio with ventilation openings in high heat and density are shown in Figure 2. In hot summer, the thermal environment in the studio with better natural ventilation was relatively sultry and uncomfortable. The dual or multi-coupling environmental treatments were proposed, as listed in Table 1.

4.1. Scheme 1: working condition coupled fans with ventilation openings

As shown in Table 1, the two electric fans were uniformly suspended from the ceiling of the studio, and the heat sources are shown in Table 3. When the ambient temperature was 30°C, the flow field of Scheme 1 was obtained by numerical simulation. Figure 3 shows the air velocity profile in the lengthwise section of the studio at X = 0 m. As can be seen from Figure 3, under the action of ceiling fans, indoor air turbulence and convective heat transfer on the surface of human body were enhanced. Therefore, ceiling fans can improve the thermal comfort to a certain extent. Figure 4 shows a cross section of the temperature and velocity profile at Y = 1.1 m away from the interior floor, which was the head position of the individual.
while seated. It can be seen from Figure 4(a) that local heat was concentrated near the human body, triggered by laptop heat dissipation, human heat dissipation etc. The indoor temperature was evenly distributed, with a range of about 30.5°C–31.5°C. It can be seen from Figure 4(b) that air movement was quite intense when indoor air was simultaneously driven by natural ventilation and electric fans. Three large vortexes were seen from the velocity field, and the wind speed in the area near people was also about 0.4 m/s.

Figure 5 shows the isogram of air age in the respiratory area. As can be seen from Figure 5, the average indoor air age was between 250 and 550, indicating that the ventilation effect of the studio was very prominent. People in the southern district enjoyed

![Figure 5. Isogram air age diagram in the respiratory area.](image)

![Figure 6. Iso-PMV diagram in the respiratory area.](image)

![Figure 7. Air velocity profile in the lengthwise section (X = 0 m).](image)

(a) Scheme 2 layout  
(b) Scheme 3 layout  
(c) Scheme 4 layout
relatively fresh air because indoor air was ventilated through the two ventilation openings, while the south vent is lower than the north side. The cold air in the room sank while the hot air rose. Therefore, the south ventilation opening was dominated by intake air, while the north one was dominated by exhaust air.

The iso-PMV diagram in the respiratory area is shown in Figure 6. As can be seen from Figure 6, PMV values in most of the indoor areas were between 1.5 and 2.0. The studio was well ventilated by natural vents and fans. When the indoor temperature was higher than the outdoor temperature, a small part of the indoor heat was ventilated to the outside. However, due to the high outdoor temperature and high indoor cooling load, the overall thermal environment of the studio was still not optimistic.

The experimental results in this part are summarized as follows. For naturally ventilated rooms with a large indoor cooling load in summer, the reasonable arrangement of fans can enhance the ventilation capacity and create a certain wind speed in the working area, thus creating a more comfortable working environment for staff.

4.2. Schemes 2–4: working condition coupled air conditioning with ventilation openings

In summer, air conditioners are a kind of widely used air handling equipment, which can reduce the indoor temperature. To study the effectiveness of air conditioner coupled with, ventilation openings on the thermal environment, the indoor units of air conditioning were respectively arranged on the different walls of the studio with air vents, and the specific layouts are shown in No. 2, No.3 and No.4 of Table 1. In coupled ventilation of air conditioning, part of the cooling in the room was lost through the ventilation openings, but it ensured the hygienic requirements of personnel indoor. By adjusting the installation position of air conditioning, the optimal indoor thermal environment with the same energy consumption was obtained, and the relationship between the natural exhaust outlet and the optimal position of air conditioning was analyzed.

When the indoor air-conditioning units were placed in different positions in the studio, it was found by simulation that the indoor temperature profile was relatively uniform, but the velocity profile was quite
different. Figure 7 shows the variation of indoor air velocity along the long side of the studio. Obviously, indoor wind velocity distribution of the air-conditioner was more uniform than that of electric fans (as shown in Figure 3). The air conditioning in schemes 2 or 4 was installed along the long side of the room, and the air distribution in the studio was more uniform than that in scheme 3 (arranged along the short side).

Figure 8 is the age of air distribution of air conditioning and ventilation openings coupled models at \( X = 0 \) m, Figure 8(a) is for Scheme 2, Figure 8(b) is for Scheme 3, and Figure 8(c) is for Scheme 4. It can be seen from Figure 8 that the indoor age of air in schemes 2–4 was generally smaller than the working condition of electric fans (Scheme 1), indicating that the ventilation rate of air conditioning in the naturally ventilated studio was relatively large. There are several reasons: 1. The indoor temperature was reduced by air conditioning, which increased the temperature difference between indoor and outdoor, and the ventilation effect was strengthened by hot pressure; 2. Since the air supply direction of the air conditioner remained unchanged, it was easier to form a stable airflow direction than that of the fan rotating air supply condition of electric fans. As seen from Figure 8(a,b), when the air conditioner was installed on the east or west side of the studio, the age of air at the northernmost working area of the room was larger. As manifested in Figure 8(c), the air age of the two southernmost workers is higher than that of other workers in Scheme 4.

Figure 9 shows the variation curve of PMV index at the height of 1.1 m away from the indoor floor in
Schemes 2–4, which was the head position of the individual while seated. It can be seen from Figure 9 (a,b) that staff on the installation side of the air conditioner in schemes 2 and 3 were less comfortable than those sitting in the opposite. According to Figure 9(c), the air supply direction of Scheme 4 is consistent with the prevailing wind direction of the studio, making the indoor PMV index more evenly distributed. In general, the PMV value of Scheme 4 was lower than that of Scheme 2 and Scheme 3.

By analyzing the indoor thermal environment of three air-conditioned coupled natural ventilation schemes, the results show that Scheme 4 was superior to Scheme 2 and Scheme 3. Although there was little

![Figure 12](image12.png)

(a) Scheme 5 layout (b) Scheme 6 layout (c) Scheme 7 layout

*Figure 12. Age of air distribution map at Y = 1.1 m.*

![Figure 13](image13.png)

(a) Scheme 5 layout (b) Scheme 6 layout (c) Scheme 7 layout

*Figure 13. PMV contour map at Y = 1.1 m.*
4.3. Schemes 5–7: air-conditioner, ceiling fan and vents coupled working condition

In order to study the thermal environment of a studio with ceiling fans, air conditioners and ventilation openings, a studio model of the installation position of three air treatment equipment was established, as shown in Table 1. The air vents and ceiling fans in the working room were fixed. Ventilation openings were located on the north and south walls of the studio, and two fans hung evenly from the ceiling of the studio. The air-conditioning indoor units were installed at the middle distance of the east, west and south walls at the height of 2.4 m above the floor in No. 5 ~ 7. By studying the above three schemes, the optimal indoor thermal environment under the coupling effect of natural ventilation, fan and air conditioning under the same energy consumption was obtained, and the optimal installation scheme of air treatment equipment under such condition was also obtained.

Figure 10 shows the flow velocity profile on the section at the short side central axis of the studio under the triple coupling of ventilation, ceiling fan and air conditioning. As can be seen from Figure 10, no matter on which wall the air-conditioned indoor unit was installed, the air-conditioned air supply played a key role in the indoor airflow distribution. However, the air distribution in the workspace was more uniform than that in a naturally ventilated workplace with only fans or air conditioners, because the rotating wind generated by fans and the effect of natural ventilation interfered with the air supply of air conditioners.

Figure 11 shows the temperature nephogram of the studio at the height of 1.1 m. It can be seen from Figure 11 that the average indoor temperature of scheme 7 with air-conditioning on the south wall was 0.5–1 °C lower than that of schemes 5 and 6 with air-conditioning on the east wall. Figure 12 shows that the air age in Scheme 7 was relatively lower than that in schemes 5 and 6, and air quality was also better.

Figure 13 shows the PMV contour at the height of 1.1 m from the interior floor of the studio. Figure 13 (a,b) respectively shows PMV isolation when the air conditioner was symmetrically installed on the east and west walls, and PMV distributions in the two cases had little difference due to the influence of ventilation openings set up asymmetrically on the north and south walls of the studio. Figure 13(c) shows the PMV contour map of the air conditioner installed on the south wall of the studio. According to the figure, the thermal comfort in Scheme 7 was superior to other schemes.

Results of schemes 5, 6 and 7 of air conditioning and ceiling fan coupled by natural vents illustrate that air-conditioning south wall layout was superior to east and west wall layout. In the air-conditioning-ceiling fan-natural ventilation coupling work scheme, due to the uniform rotating wind generated by the fan, the indoor airflow distribution was more uniform than that in schemes 2–4 (air conditioning + natural ventilation), and indoor comfort was also stronger. Indoor air quality was perfect because of the large temperature difference between indoor and outdoor, and increased natural ventilation. At the same time, the air flow between the two ventilation openings was also formed. When the air supply direction of air conditioning was consistent with the prevailing wind direction, the low-temperature air supply of the air conditioning was more likely to reach all parts of the room. Moreover, indoor air disturbance was enhanced by the air supply of fan and air conditioning, thus improving the thermal comfort of humans. Therefore, when the air conditioner and ceiling fan were coupled with the natural ventilation, the optimal position of the air conditioner was on the same side with the natural ventilation opening for the sake of both energy saving and thermal comfort.

5. Conclusions

This paper aims at providing an energy-saving and efficient air distribution scheme to improve the indoor environment of a naturally ventilated room with high personnel density, large fresh air load, large envelope load and large indoor heat dissipation. The studio with ventilation openings, which was temporarily reconstructed from an ordinary classroom, was selected as the object of this study. Numerical simulation and chamber tests with human subjects were used in these studies. The tests were carried out on by multi-dimensional coupled environmental treatment methods. The experiment includes three different air distribution modes: the joint action of fan and vent, the joint action of air conditioner and vent, and the coupling of air conditioner and ceiling fan with natural vent. By studying the flow field, temperature field, the distribution of air age and PMV formed by various
working conditions, the optimal air-distribution scheme was obtained. The experimental results are summarized as follows.

- In the working condition of the fan coupled with ventilation openings, the reasonable installation of fans can enhance the ventilation capacity and create a certain wind velocity in the working area, thus creating a more comfortable working environment for staff.
- In the working conditions of air conditioning coupled with ventilation openings and air conditioning and ceiling fans coupled by ventilation openings, the optimal position of the air conditioner was on the same side with the natural ventilation opening for the sake of both energy saving and thermal comfort.

The results show that in different air distribution schemes in natural exhaust rooms, the air direction between natural exhaust outlets has a crucial influence on the installation location of other air processing equipment. Only when the air supply direction of the fan or air conditioner is consistent with the prevailing wind direction of the room, indoor air distribution will be more uniform and indoor thermal comfort will be tremendously enhanced.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

Bojic, M., F. Yik, and T. Y. Lo. 2002. “Locating Air-conditioners and Furniture inside Residential Flats to Obtain Good Thermal Comfort.” Energy and Buildings 34 (7): 745–751. doi:10.1016/s0378-7788(01)00143-8.

Chen, Y. C., S. Y. Chang, C. H. Cheng, and C. C. Wu. 2018. “Influencing Factors and Improvement Strategies for Indoor Air Quality and Human Thermal Comfort in a Convenience Store.” Health 10 (2): 215–227. doi:10.4236/health.2018.102018.

He, L., B. Lei, H. Bi, and T. Yu. 2016. “Simplified Building Thermal Model Used for Optimal Control of Radiant Cooling System.” Mathematical Problems in Engineering 2016 (pt2): 1–15. doi:10.1155/2016/2976731.

Homod, R. Z., K. S. M. Sahari, and H. A. F. Almurib. 2014. “Energy Saving by Integrated Control of Natural Ventilation and HVAC Systems Using Model Guide for Comparison.” Renewable Energy 71 (November): 639–650. doi:10.1016/j.renene.2014.06.015.

Jia, C., and D. Sun. 2018. “Analysis of Energy-saving by Using Electric Fans to Assist Air Conditioners in Environmental Control.” IPPA Quarterly Journal of Indian Pulp and Paper Technical Association 30 (1): 311–316.

Li, N., and Q. Chen. 2020. “Study on Dynamic Thermal Performance and Optimization of Hybrid Systems with Capillary Mat Cooling and Displacement Ventilation.” International Journal of Refrigeration 110: 196–207. doi:10.1016/j.ijrefrig.2019.10.016.

Lin, Z., T. T. Chow, K. F. Fong, Q. Wang, and Y. Li. 2005. “Comparison of Performances of Displacement and Mixing Ventilations. Part I: Thermal Comfort.” International Journal of Refrigeration 28 (2): 288–305. doi:10.1016/j.ijrefrig.2004.04.006.

Lu, S., K. Fang, Y. Qi, and S. Wei. 2015. “Influence of Natural Ventilation on Thermal Comfort in Semi-open Building under Early Summer Climate in the Area of Tropical Island.” Procedia Engineering 121: 944–951. doi:10.1016/j.proeng.2015.09.060.

Luo, M., B. Cao, J. Damiens, B. Lin, and Y. Zhu. 2015. “Evaluating Thermal Comfort in Mixed-mode Buildings: A Field Study in A Subtropical Climate.” Building and Environment 88 (June): 46–54. doi:10.1016/j.buildenv.2014.06.019.

Meng, X., Y. Wang, T. Liu, X. Xing, Y. Cao, and J. Zhao. 2016. “Influence of Radiation on Predictive Accuracy in Numerical Simulations of the Thermal Environment in Industrial Buildings with Buoyancy-driven Natural Ventilation.” Applied Thermal Engineering 96: 473–480. doi:10.1016/j.applthermaleng.2015.11.105.

Mukhtar, A., M. Z. Yusoff, and K. C. Ng. 2019. “The Potential Influence of Building Optimization and Passive Design Strategies on Natural Ventilation Systems in Underground Buildings: The State of the Art.” Tunnelling and Underground Space Technology 92: 103065. doi:10.1016/j.tust.2019.103065.

Omran, S. V. Garcia-Hansen, B. R. Capra, and R. Droegemuller. 2017. “Effect of Natural Ventilation Mode on Thermal Comfort and Ventilation Performance: Full-scale Measurement.” Energy and Buildings 156 (December): 1–16. doi:10.1016/j.enbuild.2017.09.061.

Pan, C. S., H. C. Chiang, H. C. Yen, and C. C. Wang. 2005. “Thermal Comfort and Energy Saving of a Personalized Pfcu Air-conditioning System.” Energy and Buildings 37 (5): 443–449. doi:10.1016/j.enbuild.2004.08.006.

Park, B., and S. Lee. 2020. “Investigation of the Energy Saving Efficiency of a Natural Ventilation Strategy in a Multistory School Building.” Energies 13 (7): 1–13. doi:10.3390/en13071746.

Piselli, C., M. Prabhakar, A. De Gracia, M. Saffari, A. L. Pisello, and L. F. Cabeza. 2020. “Optimal Control of Natural Ventilation as Passive Cooling Strategy for Improving the Energy Performance of Building Envelope with PCM Integration.” Renewable Energy 162: 171–181. doi:10.1016/j.renene.2020.07.043.

Polak, J., A. Afshari, P. Sadeghian, C. Wang, and S. Sadrizadeh. 2019. “Improving the Performance of Heat Valve Ventilation System: A Study on the Provided Thermal Environment.” Building and Environment 164: 106338. doi:10.1016/j.buildenv.2019.106338.

Putra, J. C. P. 2017. “A Study of Thermal Comfort and Occupant Satisfaction in Office Room.” Procedia Engineering 170: 240–247. doi:10.1016/j.proeng.2017.03.057.

Roghanchi, P. K., K. C. Kocsis, and M. Sunkap. 2017. “Sensitivity Analysis of the Effect of Airflow Velocity on the Thermal Comfort in Underground Mines.” Journal of Sustainable Mining 15 (4): 175–180. doi:10.1016/j.jsm.2017.03.005.

Schiavon, S., B. Yang, Y. Donner, W. C. Chang, and W. W. Nazaroff. 2017. “Thermal Comfort, Perceived Air Quality and Cognitive Performance When Personally...
Controlled Air Movement Is Used by Tropically Acclimatized Persons." *Indoor Air* 27 (3): 690–702. doi:10.1111/ina.12352.

Sekhar, S. C., and C. S. Ching. 2002. "Indoor Air Quality and Thermal Comfort Studies of an Under-floor Air-conditioning System in the Tropics." *Energy and Building* 34 (5): 431–444. doi:10.1016/S0378-7788(01)00128-1.

Sekhar, S. C., and C. S. Ching. 2002. "Indoor Air Quality and Thermal Comfort Studies of an Under-floor Air-conditioning System in the Tropics." *Energy and Building* 34 (5): 431–444. doi:10.1016/S0378-7788(01)00128-1.

Tablada, A., F. De Troyer, B. Blocken, J. Carmeliet, and H. Verschure. 2009. "On Natural Ventilation and Thermal Comfort in Compact Urban Environments - the Old Havana Case." *Building and Environment* 44 (9): 1943–1958. doi:10.1016/j.buildenv.2009.01.008.

Takasu, M., R. Ooka, H. B. Rijal, M. Indraganti, and M. K. Singh. 2017. "Study on Adaptive Thermal Comfort in Japanese Offices under Various Operation Modes." *Building and Environment* 118 (June): 273–288. doi:10.1016/j.buildenv.2017.02.023.

Tian, G., Y. Fan, H. Wang, K. Peng, X. Zhang, and H. Zheng. 2020. "Studies on the Thermal Environment and Natural Ventilation in the Industrial Building Spaces Enclosed by Fabric Membranes: A Case Study." *Journal of Building Engineering* 32: 101651. doi:10.1016/j.jobe.2020.101651.

Wang, B., and A. Malkawi. 2019. "Design-based Natural Ventilation Evaluation in Early Stage for High Performance Buildings." *Sustainable Cities and Society* 45: 25–37. doi:10.1016/j.scs.2018.11.024.

Wang, Y., X. Meng, X. Yang, and J. Liu. 2014. "Influence of Convection and Radiation on the Thermal Environment in an Industrial Building with Buoyancy-driven Natural Ventilation." *Energy and Buildings* 75: 394–401. doi:10.1016/j.enbuild.2014.02.031.

Xu, X., Q. Jia, Z. Xu, B. Zhang, and X. Guan. 2016. "On Joint Control of Heating, Ventilation, and Air Conditioning and Natural Ventilation in a Meeting Room for Energy Saving." *Asian Journal of Control* 18 (5): 1781–1804. doi:10.1002/asjc.1260.

Yang, B., S. Schiavon, C. Sekhar, D. Cheong, K. W. Tham, and W. W. Nazaroff. 2015. "Cooling Efficiency of a Brushless Direct Current Stand Fan." *Building and Environment* 85 (February): 196–204. doi:10.1016/j.buildenv.2014.11.032.

Yoon, N., L. K. Norford, A. Malkawi, H. Samuelson, and M. A. Piette. 2020. "Dynamic Metrics of Natural Ventilation Cooling Effectiveness for Interactive Modeling." *Building and Environment* 180: 106994. doi:10.1016/j.buildenv.2020.106994.