A Strategy to Maximally Utilize Outdoor Air for Indoor Thermal Environment

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Abstract: In order to reduce the energy consumption of HVAC systems in buildings, the use of energy-saving solutions is necessary. One of these solutions is ventilation, which is usually used for maintaining acceptable indoor air quality and thermal comfort. As the change in outdoor environment is unpredictable and the occupant control is spontaneous, it is critical to control the windows and HVAC systems to achieve a maximum use of outdoor air for indoor ventilation. A new rule-based control strategy that could change the opening factor of windows is proposed in this study and its effectiveness was tested in five representative climates, ranging from a subtropical region to a severely cold region. A building model was set up and the indoor air temperature and energy consumption were predicted using EnergyPlus. The results show that the proposed control strategy can utilize ventilation to maintain a comfortable indoor environment with an annual uncomfortable percentage in an occupied period lower than 5%, thus leading to an energy-saving rate of 13.5–55.6%. The simulation results indicate that there are periods of ventilation available during the summer in climate zones with hot summers and warm winters, whereas the control strategy has a better energy-saving performance in temperate areas. This study conducted a preliminary exploration for practical applications of the combined operation of controllable natural ventilation and HVAC systems in buildings.

Keywords: ventilation strategy; rule-based control; indoor thermal comfort; building performance simulation

1. Introduction

Natural ventilation is an efficient passive design solution that can remove extra heat and pollutants from the indoor environment via indoor and outdoor air exchange through open windows or doors \cite{1,2}. It provides a method for occupants to adjust the indoor thermal conditions and to improve their thermal comfort \cite{3}. In addition, there is sufficient cooling energy in outdoor air that can be used to cool the indoor air of buildings \cite{4}, thereby saving on cooling energy \cite{5}.

As global warming worsens, making use of cooling energy can reduce the natural resource consumption \cite{6} and greenhouse gas emissions related to buildings \cite{7}. However, the performance of natural ventilation is highly dependent on the building design, such as building orientation, window size, and opening position, as well as on the outdoor conditions, such as the air temperature, wind speed, and wind direction \cite{3}. Several kinds of components and constructions, such as wind cowls \cite{8}, wind catchers \cite{9}, Trombe walls \cite{10}, and double-skin façades \cite{11}, have been designed and used to reinforce natural ventilation and to extend the serving time of natural ventilation.

Although natural ventilation has great potential to reduce building energy consumption and to improve indoor thermal comfort \cite{12}, the improper operation of windows
and HVAC systems may cause energy waste and excessive discomfort. Studies have shown that occupant control cannot properly respond to the complicated and dynamic ambient environment [13] and is unable to maintain the indoor air temperature within a comfortable range at all times [14]. Since spontaneous occupant control generally shows suboptimal performance in terms of energy saving and thermal comfort, advanced control strategies have been proposed to better exploit the natural ventilation potential in buildings. Han et al. [15] proposed a novel reinforcement learning method for the advance control of window opening and closing by observing and learning from the environment. The performance of natural ventilation is highly dependent on the building design and outdoor environment conditions; thus, natural ventilation is not reliable enough. Wan et al. [16] proposed an energy-efficient air-conditioning system with a fan by suppling more fresh air in periods during intermediate seasons. However, mechanical ventilation by fan cannot make use of the driving force of natural ventilation, which can save energy. Mixed ventilation integrates the advantages of mechanical and natural ventilation. Chen et al. [17] utilized a model-free Q-learning RL algorithm to design an optimal control schedule for HVAC and window systems while minimizing energy consumption and maximizing thermal comfort. In the above studies, window control in the natural ventilation model involved opening and closing, and the window opening factor could not be adjusted according to the variable outdoor environment and needs of indoor thermal comfort. Belleri et al. [18] analyzed and implemented the rule-based control (RBC) ventilation cooling strategy in a market to exploit the openings and skylight. The opening factor of the openings and skylight could be switched between 0, 0.2, and 0.4 according to the outdoor temperature. Opening factor was adjustable in this study but not flexible enough.

It has been found that natural ventilation controlled by an occupant causes indoor thermal discomfort. Natural ventilation is unreliable, and there is room for improvement in the energy-saving performance of mechanical ventilation. Existing mixed ventilation control strategies pay more attention to window operation schedules, whereby the opening factor is fixed or not flexible enough. To address these issues, this research proposes a new energy-saving rule-based control strategy that can automatically control the opening factor of windows, the air flow rate of the supply fan, and the on/off state of the air conditioner to maintain indoor thermal comfort. This strategy is very friendly to the energy-saving renovation of old houses, because there are slight requirements in terms of the information level of the building. A preliminary exploration was carried out into the mixed-ventilation control strategy using a variable window opening factor.

In this ventilation strategy, the cooling load of the controlled room was calculated to determine the required ventilation rate, based on the current indoor and outdoor conditions. The opening factor of exterior windows, the air flow rate of the supply fan, and the on/off status of the air conditioner were regulated according to the required ventilation rate. The ventilation performance, energy-saving performance, and thermal comfort performance of the proposed strategy were examined using an energy simulation via EnergyPlus.

2. Methods

2.1. Dynamic Thermal Model

The dynamic thermal model is based on the energy conservation law. In order to simplify the model, it was assumed that the interior of the room was thermally homogeneous. According to the energy conservation law, the increase in heat that needs to be discharged to the outdoors compared with the previous moment can be expressed as:

\[ \Delta Q = C dT_i = C \frac{T_{i,1} - T_{i,2}}{\Delta t} \]  

(1)

where \( \Delta Q \) is the increased amount of heat that needs to be released to the outdoors (W), \( C \) is the mean thermal capacity of the room (J/m\(^2\) °C), \( T_{i,1} \) is the indoor temperature at the current timestep (°C), \( T_{i,2} \) is the indoor temperature at the previous timestep (°C), and \( \Delta t \) is the length of one timestep (s).
2.2. Airflows Driven by Thermal Buoyancy and Wind

Empirical expressions for calculating the airflow through openings in single-sided natural ventilation were previously investigated and developed. De Gids and Phaff performed full-scale experiments in 1982 considering the effect of both wind and thermal buoyancy, as well as turbulence [19]. According to their experimental results, the following expression was obtained:

\[ U_m = \sqrt{(C_1 U_{10}^2 + C_2 h \Delta T + C_3)}, \]  

(2)

where \( U_m \) is the mean air velocity in an opening (m/s), \( U_{10} \) is the mean wind speed at \( h = 10 \text{ m} \) (m/s), \( h \) is the height of the opening (m), \( \Delta T \) is the air temperature difference (°C), \( C_1 \) is a dimensionless coefficient depending on the wind effect, \( C_2 \) is the buoyancy constant, and \( C_3 \) is the turbulence constant.

The constants were obtained as a best fit to the experiments, as described below.

\[ U_m = \sqrt{(0.001 U_{10}^2 + 0.0035 h \Delta T + 0.01)}. \]  

(3)

2.3. Required Ventilation Rate and Opening Factor of Window

According to the energy balance equation and mass balance equation, the required ventilation rate to maintain indoor temperature at the current timestep \( q_1 \) can be expressed as

\[ q_1 = \frac{\Delta Q}{(T_{i,1} - T_{o,1}) \times \rho_{\text{air}} \times c_{\text{air}}} + q_2, \]  

(4)

where \( q_1 \) is the required ventilation rate at the current timestep (m\(^3\)/s), \( T_{o,1} \) is the outdoor air temperature at the current timestep (°C), \( \rho_{\text{air}} \) is the density of air (kg/m\(^3\)), \( c_{\text{air}} \) is the heat capacity of air (J/(kg °C)), and \( q_2 \) is the required ventilation rate in the previous timestep (m\(^3\)/s).

The opening factor of the exterior window can be expressed as

\[ OF = \frac{q_1}{U_m \times A_{\text{effect}}}, \]  

(5)

2.4. Thermal Comfort Model

The present study applied EN 16798-1:2019 [20] adaptive thermal comfort model, which was proposed by Nicol and Humphreys in 2002 [21], in a mixed-mode building on the basis of previous studies. While this model is meant for naturally ventilated spaces without mechanical cooling and heating systems, Kim et al. found that the adaptive comfort standard is suitable to mixed-mode buildings, especially during the natural ventilation operation period [22]. Parkinson et al. found good agreement of comfort temperatures between naturally ventilated buildings and mixed-mode buildings in their study [23].

The upper and lower temperature limits of the comfort zone and the optimal operative temperature can be calculated using the following equations:

\[ T_{i-\text{max}} = 0.33 \cdot T_{rm} + 18.8 + K, \]  

(6)

\[ T_{i-\text{min}} = 0.33 \cdot T_{rm} + 18.8 - K, \]  

(7)

\[ T_c = 0.33 \cdot T_{rm} + 18.8 \]  

(8)

where \( T_{i-\text{max}} \) is the upper air temperature limit of the comfort zone (°C), \( T_{i-\text{min}} \) is the lower air temperature limit of the comfort zone (°C), \( T_c \) is the optimal operative temperature (°C), \( T_{rm} \) is the outdoor running mean air temperature (°C), and \( K \) is a constant depending on the required comfort category (\( K = 2 \) for comfort category I, \( K = 3 \) for comfort category II, and \( K = 4 \) for comfort category III).
Below an outdoor running mean air temperature of 10 °C, the upper temperature limit was set as the upper temperature limit for heating, as recommended by EN 16798-1:2019. Below an outdoor running mean air temperature of 15 °C, the lower temperature limit was set as the lower temperature limit for heating, as recommended by EN 16798-1:2019.

2.5. Prediction of Indoor Air Temperature

In the control strategy proposed in this article, it is assumed that the air temperature will change uniformly in a short time in the future, following the trend of its previous period. The opening factor and air flow rate change only when the predicted value of indoor air temperature is beyond the thermal comfort zone. In this way, changes in the window opening factor and the air flow rate of the air supply fan can be reduced. The predicted indoor temperature can be calculated using the following equation:

\[
T_{\text{pre}} = T_{i1} + \frac{T_{i1} - T_{i2}}{\Delta t} \times t_{\text{pre}},
\]

where \( T_{i1} \) is the temperature at the current timestep (°C), \( T_{i2} \) is the temperature at the former timestep (°C), \( \Delta t \) is the time length of the timestep (s), \( t_{\text{pre}} \) is the time length for the prediction (s), and \( T_{\text{pre}} \) is the predicted temperature after \( t_{\text{pre}} \) (°C).

2.6. Rule-Based Model

In this paper, a rule-based model was established according to the EN 16798-1:2019 standard adaptive thermal comfort model. The rule-based model was customized to prioritize natural ventilation over mechanical ventilation, while improving building performance. The operable window based on the rule model is shown in Figure 1.

![Figure 1. The control logic of the rule-based model; \( q_{\text{fan-max}} \) is the maximum air flow rate of the supply fan, which was set to 0.075 m\(^3\)/s in this study.](image)
There are three actuators in the control system that control the opening factor of the window, air flow rate of supply fan, and on/off status of the air conditioner. The control system works when the room is occupied. Note that the conditions in Figure 1 are defined for each timestep (i.e., 1 min). $T_{pre}$ is calculated if the room is occupied. The system does not change if $T_{pre}$ is in the comfort zone, which reduces the operation of the system components. If $T_{pre}$ is out of the comfort zone, the system evaluates whether the outdoor air temperature is suitable for natural or fan-based ventilation. Držík and Mihálik [24] measured the coefficient of convection heat transfer with a low temperature difference and found that the coefficient increased by 25% when the temperature difference increased from 2 °C to 4 °C. Large differences in the indoor and outdoor temperature can enhance the flow rate of natural ventilation [25] and can improve the energy performance of ventilation [26,27]. Thus, a certain air temperature difference is needed for indoor and outdoor heat exchange, whereby ventilation is only activated when the difference between indoor air temperature and outdoor air temperature is greater than 3 °C, according to Artmann’s research [28]. Windows are operated if the calculated opening factor is smaller than 1.0. A variable volume supply fan is activated if the opening factor is greater than 1.0 and the required ventilation rate is smaller than the maximum flow rate the fan can provide—referred to as fan-based ventilation in this study. The air conditioner works when the fan cannot supply the required ventilation rate and when the indoor air temperature is outside of the comfort zone, which means the ventilation control strategy is unable to maintain indoor thermal comfort by inducing outdoor air into the room.

2.7. Description of Model

To evaluate the ventilation and energy-saving performance of the proposed control strategy in office buildings, a typical office model in a mixed-mode building was set up and simulated for five major cities within five different climate zones in China (Table 1). The office model was created in OpenStudio and was simulated using the commercial software EnergyPlus. The dimensions of the office were $W \times L \times H = 3.0 \times 3.0 \times 3.0$ m, with a window ($W \times H = 2.0 \times 1.8$ m) located in the center of the south wall. The height of the windowsill was 0.85 m (Figure 2), equivalent to a window-to-wall area ratio of 40%. The maximum opening area of the window was set to 1.8 m$^2$, equal to half of the window area.

| Climate Zone                              | City, Province          |
|-------------------------------------------|-------------------------|
| Severely cold climate                     | Urumqi, Uygur           |
| Cold climate                              | Beijing, Beijing        |
| Hot summer, cold winter climate           | Shanghai, Shanghai      |
| Hot summer, warm winter climate           | Guangzhou, Guangdong    |
| Mild climate                              | Kunming, Yunnan         |

Two different thermal boundary conditions in the building envelope are simulated. The cases with the boundary conditions as outdoor environment are simulated to show the operation of the rule-based control strategy in an individual building, and cases with the boundary conditions as adiabatic except for the south wall are simulated to illustrate the energy performance of the rule-based control strategy in the rooms in the internal zone of a building. The total equivalent U-factor of the façade, including the window and exterior wall, and the solar heat gain coefficient (SHGC) of the window were specified in accordance with GB 50189-2015 [29] in the five climate zones (Table 2).

The opening of windows introduced outdoor air into the office through natural ventilation, which was the main cooling strategy. Both the natural ventilation rate and the infiltration rate into the office were calculated using the Air Flow Network model in EnergyPlus. The infiltration air mass flow coefficient and air mass flow exponent were set to 0.002 and 0.65, respectively.
Table 2. Building envelope properties defined for the five climate zones according to GB 50189-2015.

| Climate Zone                      | Exterior Wall U-Factor (W/m²K) | Roof U-Factor (W/m²K) | Window |
|-----------------------------------|---------------------------------|------------------------|--------|
| Severely cold climate             | 0.38                            | 0.28                   | U-factor = 2.4  |
|                                   |                                 |                        | SHGC = 0.48  |
| Cold climate                      | 0.45                            | 0.4                    | U-factor = 2.2 |
|                                   |                                 |                        | SHGC = 0.48  |
| Hot Summer, cold winter climate   | 0.8                             | 0.5                    | U-factor = 2.6 |
|                                   |                                 |                        | SHGC = 0.4   |
| Hot summer, warm winter climate   | 1.5                             | 0.8                    | U-factor = 3  |
|                                   |                                 |                        | SHGC = 0.35  |
| Mild climate                      | 1.5                             | 0.8                    | U-factor = 3  |
|                                   |                                 |                        | SHGC = 0.4   |

The supply fan was activated to cool the office when the natural ventilation was unable to offer sufficient outdoor air. The maximum air flow rate of the supply fan was set to 0.075 m³/s. The window would be closed when the supply fan was activated.

A packaged terminal heat pump (PTHP) system was used as an air conditioner in EnergyPlus to supply conditioned air into the office as required to maintain the indoor air temperature setpoint. The cooling and heating setpoints were the optimal operative temperature $T_c$. But the cooling setpoint was below 28 °C according to EN 16798-1:2019. The window and supply fan were closed when the PTHP was working.

The light power intensity was set to 9 W/m² and the electric equipment power intensity was set to 15 W/m² and 50 W/m² during the occupied period. The working schedule of the office was from 9:00 a.m. to 6:00 p.m., during which two people worked in the office. The total heat gain from the occupants was automatically calculated by EnergyPlus. The sensible heat increment was composed of 30% radiant type and 70% convective type. The rule-based control strategy was implemented in the energy management system (EMS).

3. Results and Discussion

3.1. Operation of Control Strategy

Figure 3a,b show the simulation results of indoor temperature, window opening factor, fan air mass flow rate, and air conditioner on/off status according to the rule-based ventilation control strategy and outdoor temperature in a mild climate zone on 18 March and 18 May with a 15 W/m² indoor equipment load.
Figure 3. Simulation results of indoor temperature, window opening factor, fan air mass flow rate, and air conditioner on/off status according to the rule-based ventilation control strategy and outdoor temperature in a mild climate zone on 18 March and 18 May with 15 W/m² indoor equipment load: (a) 18 March; (b) 18 May.

The upper limit of the comfort zone was 26.8 °C and the lower limit of the comfort zone was 20.8 °C on 18 March according to weather data download from the EnergyPlus weather database, calculated using Equations (6) and (7). When people started working at 9:00 a.m., the indoor temperature increased rapidly and threatened to exceed the upper limit temperature of the comfort zone. Meanwhile, the outdoor temperature was 15.52 °C, which was 5 °C lower than the lower limit comfort zone. The air conditioner was turned on from 9:00 to 9:30 a.m. when ventilation was not available. A window was then opened to adjust indoor environment when the outdoor temperature rose to 15.8 °C at 9:30 a.m. The window’s opening factor increased from 47% to 54.5% as the outdoor environment became warmer and solar radiation became stronger. The window opening factor was relatively stable along with the outdoor temperature from 12:00 to 6:00 p.m. Although the temperature in the office increased gradually during this period, the indoor environment remained within the comfort zone.

The upper limit of the comfort zone was 28 °C and the lower limit of the comfort zone was 22 °C on 18 May. The window opening factor was maintained at around 60% from 9:00 a.m. to 2:30 p.m. Due to the increase in outdoor and indoor temperature and the low outdoor wind speed, ventilation was unable to adjust the indoor environment; hence, the air conditioner was turned on to control the indoor thermal environment. As the outdoor temperature decreased after 2:45 p.m., natural ventilation was activated to adjust the indoor thermal environment with the maximum window opening factor reaching 86.7%. From 5:00 p.m. to 6:00 p.m., the amount of air entering the room was insufficient and the fan was turned on to deliver outdoor air to the room to maintain indoor thermal comfort. The results in Figure 3a,b show that the proposed control strategy could automatically control the opening factor of the window, the fan air mass flow rate, and the on/off status of the
air conditioner to adjust the indoor environment according to the changes in indoor and outdoor temperature, thereby maintaining indoor thermal comfort.

3.2. Use of Ventilation

Figures 4 and 5 show the proportions of natural ventilation hours and fan-based ventilation hours in the five cities in different climate zones in China when the indoor equipment load is 50 W/m$^2$ and 15 W/m$^2$ during working hours according to the rule-based model.

As shown in Figure 4, the natural and fan-based ventilation times were concentrated in the summer and transitional seasons for cold and severely cold climate zones when the outdoor environment was warm. The average monthly ventilation time in these two climate zones was 17.2% and 14.5%, respectively.

**Figure 4.** Percentage of occupied period in each month when natural ventilation and purely fan-based ventilation were sufficient to maintain an acceptable indoor thermal environment, at an indoor equipment load of 50 W/m$^2$ in different climate zones: (a) severely cold; (b) cold; (c) hot summer cold winter; (d) hot summer warm winter; (e) mild.
Shanghai is located in the hot summer, cold winter climate zone on the coast of central and eastern China, where the calculated average annual natural and fan-based ventilation time was 30%. Compared to the cold climates, the natural and fan-based ventilation time in the transitional seasons was longer, while there was also a short period in the winter. In the hot summer, warm winter climate zone, ventilation could be used to adjust the indoor comfort throughout the year. The simulation results show that the monthly average ventilation ratio was 40.9% during working hours from October to April of the second year.

The mild climate showed the longest time of natural and fan-based ventilation due to the suitable outdoor climate. The annual average ventilation ratio in this climate was 41.1%. Even in the summer, the average time for ventilation could reach 63.2%. Meanwhile, the presence of a fan increased the length of time that the room is ventilated by outdoor air. The simulation results show that, with the help of the fan, the indoor ventilation time increased by 3.2% on average, and the highest increase was 8.4% in this region.
The time period for natural and fan-based ventilation increased when the equipment load was decreased to 15 W/m². The annual ventilation time increased by 6.6% in Beijing, 5.3% in Guangzhou, 3.6% in Shanghai, 8.7% in Kunming, and 5% in Urumqi. The length of natural ventilation increased significantly, by an average of 7% in the five climate zones, while the average length of fan-based ventilation time was decreased from 2.8% to 1.5%.

3.3. Thermal Discomfort

Figure 6 presents the simulation results of the annual discomfort hours. The discomfort hours were calculated according to the EN 15251:2007 model. The simulation results show that, except for Urumqi, which is located in the severely cold climate zone, the annual discomfort hours were on average 0.3% and 0.9%, respectively. The annual discomfort hour in Urumqi accounted for 4.6% and 3.7% in both cases. These results indicate that the rule-based control strategy can make use of outdoor air for indoor ventilation without sacrificing the indoor environment.

3.4. Energy Performance

The total annual energy consumption per area of the air conditioner with and without the rule-based control strategy with different thermal boundary conditions in building envelope is shown in Figure 7. With the rule-based control strategy, the average energy-saving rates of air conditioning were 32.2% and 30.4% when the equipment load was 50 W/m² and 15 W/m² and when the building envelope was exposed to the outdoor environment, respectively. These results indicate that when there is a large internal load in the room, the energy-saving effect of this ventilation strategy is better. The rule-based control strategy showed the greatest energy-saving potential in the mild climate zone, where the average energy-saving rate of the air conditioner reached 53.67%. Although the natural and fan-based ventilation time was short in Urumqi, the air conditioner exhibited the biggest energy-saving rate. The annual total energy consumption per unit area of the air conditioner was reduced by 26.8 kWh/m² on average in Urumqi. In addition, this control strategy led to energy-saving rates of 31.3% and 30.8% in Guangzhou and Shanghai.

Compared with the cases described above, the energy-saving performance of applying this control strategy in the internal rooms of the building is still obvious. When the indoor equipment load is 50 W/m², the energy-saving performance of the ventilation control strategy in different climate regions is similar, with an average energy-saving rate of 17.75%. When the indoor equipment load is 15 W/m², the energy-saving performance of the ventilation control strategy in different climate zones is quite different. The energy-saving rate in the mild climate zone is 40.5%, in the severe cold zone is 15%, and the average energy-saving rate in the five climate zones is 27.3%. The energy-saving performance is better under low indoor load conditions. In general, the rule-based control strategy can use outdoor air through natural and fan-based ventilation to adjust the indoor environment, thereby making use of the cooling energy potential of outdoor air.
4. Conclusions

As a passive method, ventilation can effectively reduce building energy consumption and improve indoor air quality and thermal comfort, which is very beneficial for the design of energy-saving buildings. In this study, a new rule-based ventilation control strategy was proposed to automatically control the opening factor of the window, the air flow rate of the supply fan, and the on/off status of the air conditioner according to the change in outdoor and indoor conditions, whereas existing mixed-ventilation control strategies pay more attention to window operation schedules, whereby the opening factor is fixed or not flexible enough. The opening factor of the window is flexible in this control strategy compared to traditional ventilation control strategies, in which the opening factor is considered constant for natural ventilation. The internal load change and required ventilation rate in the room were calculated and used by the control strategy to regulate the opening factor of the window, the flow rate of the supply fan, and the on/off status of the air conditioner. To evaluate the performance of the developed control strategy, the indoor air temperature and energy consumption of a typical office room located in five different climate zones of China were simulated using EnergyPlus. The cooling potential of ambient air was exploited by the ventilation strategy. The average monthly ventilation ratio varied from 14.5% in the severely cold climate zone to 40.9% in the mild climate zone, and the average monthly ventilation time ratio increased with the decrease in indoor equipment load. With the help of fan-based ventilation, the ventilation time ratio was increased by 3.2% on average in the five climate zones, and the highest increase was 8.4%
in mild climate. The simulation results show that the control strategy has good energy performance, with an average energy-saving rate of 31.3% when the building envelope is exposed to the outdoor environment, and with an average energy-saving rate of 22.6% when the building envelope is defined as adiabatic, compared to the cases without the ventilation control strategy. The simulation results also show that, with this control strategy, the percentage of annual discomfort hours during occupied periods in the five cities was lower than 5%, indicating that the rule-based control strategy saved air-conditioning energy without greatly sacrificing indoor thermal comfort.

As a limitation of this study, the developed rule-based control strategy is still a prototype and needs to be further extensively investigated. In addition, the predictions of changes in both internal cooling load and indoor air temperature in the rule-based control strategy are based on relatively simple models. The airflow rate model was limited to single-side ventilation. Moreover, the indoor air quality, which has attracted widespread attention in recent years, was not taken into consideration in the ventilation strategy. A simplified model is selected to preliminarily demonstrate its efficiency of energy saving by comparing it with the fully mechanical method. In the future, a more realistic model will be used to perform a parametric and optimal analysis of this control strategy. A more accurate building thermophysical model will be included in this rule-based control strategy to improve the predictive accuracy of changes in indoor cooling load and air temperature, which determine the required ventilation rate and ventilation mode. In addition, the developed rule-based control strategy needs to include a more precise ventilation model to fit various natural ventilation modes, such as ventilation through opened windows and ventilators. A cross-ventilation model and multi-zone ventilation model can also be applied in the control strategy to make it more practical. After the control strategy is improved, simulation shall be carried out with a more representative building energy consumption model and the control strategy will be evaluated in detail through experiments, and the influence of global climate change on the control strategy will be studied.

**Author Contributions:** Conceptualization, L.T., G.Z. and Z.A.; methodology, L.T. and G.Z.; software, L.T. and C.S.; data curation, L.T.; writing—original draft preparation, L.T. and Z.L.; writing—review and editing, G.Z. and Z.A.; project administration, G.Z. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

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