THE PERFORMANCE ANALYSIS OF NATURAL VENTILATION FOR BUILDING COOLING IN CHANGSHA CITY, CHINA[1]

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ABSTRACT

As a passive cooling strategy, natural ventilation is an energy conservation technology with great developing potential. The typical technologies of natural ventilation include night ventilation and natural ventilation with heat storing materials. The factors which affect ventilation include technique parameter, climate parameter and building's parameter. The natural ventilation in summer in a typical building in Changsha City, which locates in hot summer and cold winter area, was measured. The effects of air exchanging rate, ventilation time, the area of exterior windows and the indoor heat storing mass for the ventilation are analyzed and validated by simulation.

KEYWORDS

Natural ventilation, Night ventilation, Thermal mass, Ventilation effect

INTRODUCTION

For the shortage of energy in the world and the developing of sustainable building technology, the natural ventilation becomes to be an indispensable technology for ecological buildings and green buildings. The natural ventilation is widely used for its two functions: on one hand, it improves the indoor thermal condition for it lowers the indoor temperature, on the other hand, it improves the indoor air quality for it displaces the stale indoor air. The building can be natural ventilated all day long when the outdoor condition is favorable. When the air flow of natural ventilation is uncontrolled in summer, it may lead to very hot situation indoor. This can be settled by night ventilation. Combined night ventilation with heat storing materials, the temperature indoor during daytime won't be too high for the heat storing materials stores a great deal of heat, then the night ventilation takes away the heat of the heat storing materials so it lowers the indoor temperature and restores the heat storing ability of the heat storing materials.

Compared to the office buildings with air conditioning systems, the energy for cooling and expense for energy saved in office buildings with natural ventilation is 14~41 kWh/m^2 and 1.3~3.6 dollars/m^2, respectively[1]. It is pointed out in the summarize report (Annex35) in 2000 of international energy agency (IEA) that the building energy cost can be lowered by more than 50% if natural ventilation technology can be efficiently used[2]. Based on the climate conditions, all the countries in the world develop various building structure to enhance natural ventilation in the building. The adoption of natural ventilation in our country can be traced to ancient time. Such as courtyard house in Beijing and the caves in northwestern areas. This technique also attaches great importance in south China. The location of the doors and windows, the direction and structure of the buildings are all implicating the consideration of natural ventilation. Changsha locates in monsoon humid subtropics and has clear four seasons, cold winter and hot summer. Its winter and summer is long and autumn and spring is short. The average temperature of the whole year is 17.2℃. July is the hottest month and the average temperature is 29.4℃. The highest temperature 43℃ appeared during one year's early August. The temperature begins to increase markedly during late May. There are 85 days when the temperature is above 30℃ and about 30 days when the temperature is above 35℃. It is very hot and rains little during summer. There is a certain difference in temperature during day and night, and the southeast winds make it possible for the buildings to ventilate naturally.

The main parameters that determine the efficiency of natural ventilation can be classified in three broad groups

Climatic parameters

In natural ventilation, the outside air is induced into rooms to improve indoor environment, so the air should meet some requirements. The dry temperature, solar radiation, wind velocity etc. all affect the natural ventilation effect. And to reduce the solar radiation and indoor equipments heat can greatly

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improve indoor thermal comfort. And in summer, if the outdoor temperature range reaches 10℃, night ventilation can be used. Givoni states that the indoor maximum temperature in night ventilated building follows the outdoor diurnal temperature range. Blondeau etc. proposed that the average outdoor temperature range can be used to predict the indoor maximum temperature. And Shaviv proposed that the outdoor relative humidity should be considered in night ventilation as if air relative humidity is high, it will affect the thermal comfort.

Building parameters

In relation to building parameters, the requirement is usually a minimum amount of thermal inertia, generally defined as a minimum building mass. The existence of important thermal structural mass increases the efficiency of the technique since the inertia of the building is increased and the effect of night ventilation can be observed in the next day's indoor temperature profiles, with a lower and delayed peak indoor temperature. The thermal inertia depends on qualitative features including the type of materials that are used and their position inside the walls. The thermal effusivity b of a given material may be calculated as following:

$$b = \sqrt{\kappa \ \rho \ C_p}$$

Where the κ is the thermal conductivity of the layer material (Wm-1K-1); ρ is the density of material(kgm-3); and C_p is the specific heat of the material(J kg-1K-1).this characterizes both the damping and delay resulting. Der Maas and Roulet widened the concept as the equivalent effusivity, b_{eq} for multi-layer wall. But P. Blondeau states that it does not fully represent the building potential for night ventilation since it does not consider all the elemental heat transfer processes.

The interior planning of the building also plays a very important role, determining how unobstructed is the flow of the air through the building.

Technical parameters

The technical parameters related to natural ventilation cooling efficiency are ventilation ways, time, and the ventilation rate, that is the building operation strategy. If the building that has a parvis or atrium, natural night ventilation can be used to cooling. In other conditions, mechanical ventilation should be used. The ventilation time is dependent on the difference between indoor and outdoors. In general, the higher the ventilation rate, the better the temperature dropping. But the optimal ventilation rate is not a constant. Blondeau recommend 8-10ACH[3], and Edna Shaviv shows the 20ACH is best in his simulation[4], and in Pablo La Roche experiments, the ventilation rate is less than 5ACH[5].

This paper is the natural ventilation experiment study, including the night ventilation and all day natural ventilation. The main aim is as following:

The technical parameters such as the ventilation time and ventilation rate effect on natural ventilation cooling effect.

1. The building parameters that is thermal mass effect on natural ventilation cooling effect.

2. The simulation of natural ventilation potential and effect in hot summer and cold winter area.

EXPERIMENTAL DATA AND EVALUATION

In order to study the effect of natural ventilation, some experiments have been carried out in two office rooms in Changsha City of China.

Description of the case study building

The case study building is the Sustainable Built Environment Center in Changsha. It is an office building with three storey and the Fig.1 shows the third floor plan.

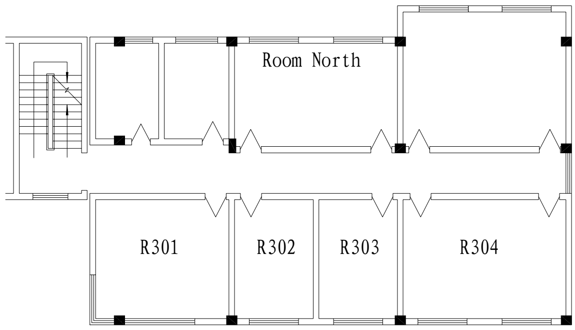

Fig.1 the third floor plan of the case study office building

The testing rooms are R302 and R303 in the third floor with same dimension. The building is a light building. The wall is a brick building, the inner surface is plastered and stuccoed and outer surface is cement mortar. The window is south faced and it is a monolayer steel window. The floor is Cast-in-place floor and over-head insulated layer. The building is 11.25m height and every storey is 3.3m and stud is 3.2m. The overall building area is 695m^2. The testing rooms R302 and R303 has the same conformation, and each has an area 17.28 m^2. The third storey is not fitment and not used before and its air conditioning system is not used before.

The experimental period is 22 September to 18 October in 2006. Before the case testing, a week pre-testing is taken to set the temperature sensors positions. The inner wall surface temperature is recorded using a Pt100 thermocouple. There are 6 thermocouples in 6 surfaces which are all set in the geometrical center point. And 7 thermocouples are set in the room median horizontal and vertical plan to measure the indoor air temperature and the relative humidity (RH). The outdoor temperature is measured by using a Pt100 thermocouple, which is enwrapped by silver paper avoiding the solar radiation. The time interval of the Intelligent Temperature Cycling Measurement Instrument is set for 30 min. All the testing data are as following: the outdoor dry temperature and the RH, the indoor dry air temperature and the RH, the surface temperature, the solar total radiant intensity, the diffuse radiant intensity, the outdoor wind speed.

Experiment scheme

In the experimental period, the system is tested with the following strategies:

CaseⅠ: To study the effect of different air change per hour (ACH) on night ventilation cooling.

Window is closed down and heat insulation. Mechanical ventilation way is used. The ventilation duration is 21:00 at night to 08:00 next morning. The ventilation rate of R302 is 6.3 ACH, and R303 is 3.0 ACH. The door and window are kept closed during this case. There is only a supply fan in the experimental room without exhaust fan. So the exhaust air through aperture by the positive pressure.

CaseⅡ: To study the effect of different ventilation time on night ventilation cooling.

The door and window are kept closed. And the windows are heat insulation. Mechanical ventilation way is used. The ventilation rate of R302 and R303 is both 3.0 ACH. The ventilation time of R302 is 20:00 at night to 08:00 next morning. And the R303 ventilation time is 22:00 at night to 08:00 next morning.

CaseⅢ: To study the effect of different window area of natural ventilation.

The door and window are kept closed. Mechanical ventilation is used all day long. And the ventilation rate of R302 and R303 is both 3.0 ACH. Half of the window of R302 is heat insulation and all the window of R303 is heat insulation.

CaseⅣ: To study the effect of different thermal mass.

The rooms are natural ventilation all day long. Both rooms have a constant 3.0 ACH with supply fan. Half of both windows are heat insulation. We place 400 pieces of clay brick in R302 and no one in Room 303.

Evaluations of the experimental data

Several tests were performed during the 26 experimental days and the results are presented here to explain the temperature decrease effect of natural ventilation strategy in Changsha. The effect of night and day ventilation strategies, different ventilation strategies and different amount of mass is modified. The room temperature is the average temperature of six sensors.

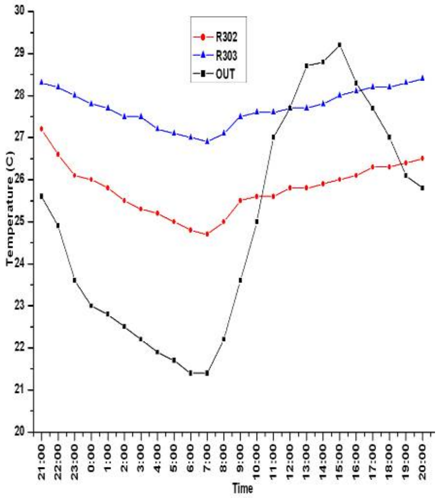

Fig.2 the temperature of R302 and R303 and outside in case Ⅰ

In case Ⅰ, the outdoor daily range is 7.8℃, the maximum is 29.2℃ and the minim is 21.4℃. Seen from Fig.2, because of the lower ventilation rate of R303 comparing to R302, the temperature of R303 is higher than R302 with a range of 1.1~2.2℃

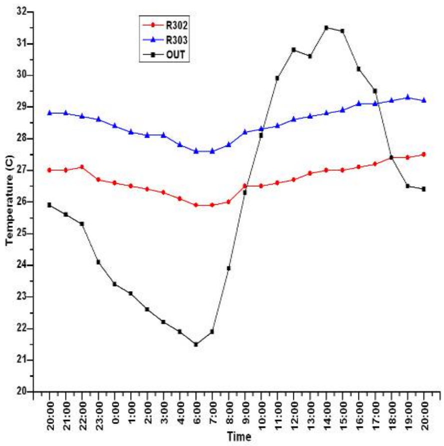

Fig.3 the temperature of R302 and R303 and outside in case Ⅱ

In case Ⅱ, the outdoor temperature daily range is 10.1℃. From 19:00, the outdoor temperature is lower than indoor temperature. As R302 started to ventilation earlier than R303, the temperature of R302 is 1.6-2.0℃ lower. From this series, we know that the longer the night ventilation time, the better the indoor temperature reduce, but the ventilation should start at the time that outdoor temperature is lower than indoor.

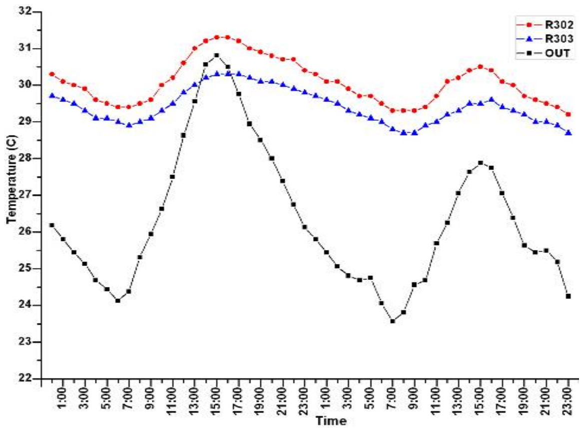

Fig. 4 the temperature of R302 and R303 and outside in caseⅢ

In case Ⅲ, 27 Sept. the outdoor temperature daily range is 6.7℃, the maximum is 30.8℃ and in 28 Sept. the outdoor temperature daily range is 5.5℃, the maximum is 28.0℃. As shown in Fig.4, the hot air come into the rooms that makes the indoor temperature rises quickly and keeps high value. The average temperature is 30.4℃ and 29.7℃, higher than the outdoor average 26.3℃. In this testing, the R302 window makes the solar internal heat enhanced, the indoor temperature arises higher. So the temperature of R302 is 0.6℃ averagely than that of R303.

From the compared to case Ⅰ, Ⅱ and Ⅲ, we can come to this conclusion: night ventilation is better than all day ventilation in day cooling. And for the window, it should be closed at day time to avoid hot air coming into rooms and advised to open at night to take advantage of cooling air.

Table 3.6 the maximum and daily range temperature of series 1~4

	Maximum temperature(℃)			Daily range(℃)		
	Out	R302	R303	Out	R302	R303
1	29.2	26.5	28.4	7.8	1.4	1.5
2	31.5	27.5	29.3	10.0	1.6	1.7
3	30.8	31.3	30.3	6.7	1.9	1.4
4	27.3	26.7	26.8	5.6	2.9	2.8

From Table1, in case Ⅰ and Ⅱ, the maximum temperature reduces as the ventilation rate increases, and the daily range depresses too. The different start time of ventilator affect the indoor temperature: it is that the earlier it operates, the lower the maximum indoor temperature and the daily range. For all-day ventilation, the maximum indoor temperature may be higher than the outdoor, and the daily range increases as the window area hoist.

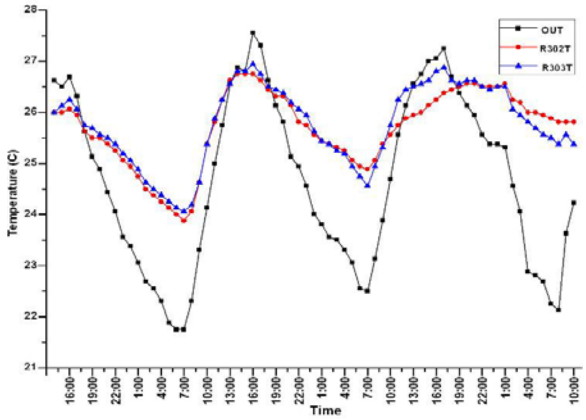

Fig. 5 the temperature of R302 and R303 and outside in caseⅣ

In caseⅣ, it is natural ventilation and the window area is 1.8375 m^2. In 15 Oct. the outdoor daily range is 5.6℃, the maximum is 27.3℃ and the minim is 21.7℃ and in 16 Oct. the outdoor daily range is 4.8℃, the maximum is 27.3℃ and the minim is 22.5℃. the minimum temperature of R302 is 2.1℃ and 2.4℃ higher than outside and the minimum of R303 is 2.3℃ and 2.1℃ higher than outside. The maximum temperature of R302 is 0.6℃ and 0.7℃ lower than outside and the minimum of R303 is 0.5℃ and 0.4℃ lower than outside. And the average temperature of R302 and R303 is both 25.7℃. And in 15 Oct. R302 is 0.2℃ lower than R303; in 16 Oct. R303 temperature is higher than R302. the daily range of R303 is bigger than R302, about 0.7℃. The thermal mass can cut down the daily range. But the experimental result is not very distinct because the outdoor temperature is 28℃ below, and the daily range is about 5.0℃, which weaken the thermal mass effect.

With the above 4 testings, we have studied the effect of ventilation rate, the ventilation time, window area and the thermal mass on night ventilation cooling. And from the analysis, we can find that as the ventilation rate increases, time becomes longer, using mechanical ventilation and put more thermal mass, the maximum temperature can be reduced, so as the daily range.

SIMULATION AND ANALYSIS

As the restriction of experimental condition and the circumstance can not be recurred, we use numerical simulation to study further the natural ventilation cooling effect. And the simulation tool is DeST—a dynamic building energy simulation tool.

DeST description

DeST(Designer's simulation Toolkits) is a building energy dynamic simulation software developed by the department of building science of Tsinghua University based on the scientific research achievement within more than ten years. The core algorithm of this software is the state space method which is based on the building heat balance and inducted into the dynamic model of the building thermal process. State space method is a dynamic model calculation method, continuous in time and discrete in space. Though the solution of the energy balance equation set of the discrete point in the room, the response coefficient to the thermal disturbance, that is the thermal performance of the room itself, can be obtained to perform the dynamic simulation of the thermal process of this room. For the integral form solution can be obtained directly using state space method, the temperature field needs no calculation and the stability and the error are independent on the time step. Therefore, compared with the traditional difference method, this method is more fast and more appropriate for the long-time and large-scale building thermal environment dynamic simulation and energy analysis.[6]

Modeling

The DeST modeling of the building is in 3 steps: establish the experimental model; validation the modeling by comparing the measured temperature and the simulation result; then using the accurate model to study more conditions to analysis the effect of natural ventilation.

The hypothesis in modeling

At the coupling calculation of the ventilation modeling and the DeST thermal modeling, the process is considered as a quasi-steady-state.

The air temperature of the room is assumed to be uniform, that is to say, it keeps the same at a certain time.

The hourly wind direction and wind speed value is the same with the dominant wind direction and outdoor wind speed in the air conditioning design handbook.

The window in the experiment is heat insulation completely; take no account of the window on indoor temperature.

The partition between two rooms is plasterboard, which is heat insulation, without regard to the interaction of the two.

Using DeST modeling the testing cases, we get the corresponding stimulant temperature data. We analyze the error between stimulant temperature Θs and measure temperature Θm. If the error is acceptable, we consider the model is an accredited model. At the same time, considering the effect of wind speed and direction, the next study is the exact model.

Error analysis of simulation relative to measurement

Comparing the change direction and the average difference between stimulant temperature Θs and measure temperature Θm and the standard deviation, we get the acceptable model. The following Fig.6 and the Table.2 are the compare results.

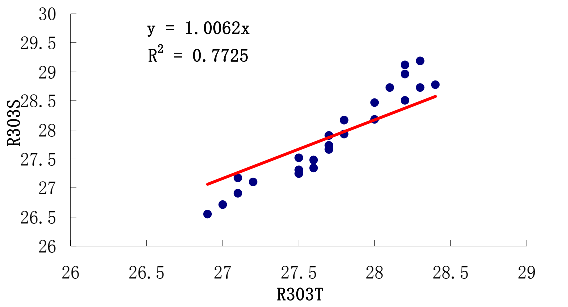

Fig.6 the stimulant and measure temperature of R303 in case Ⅰ

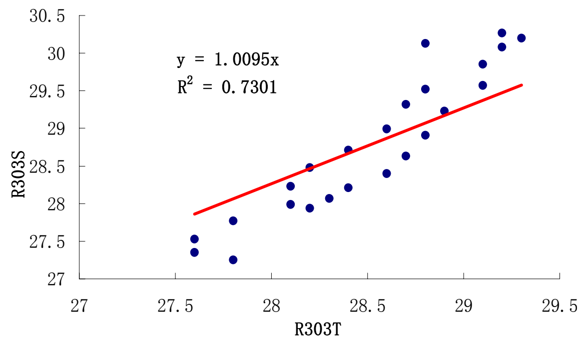

Fig.7 the stimulant and measure temperature of R303 in case Ⅱ

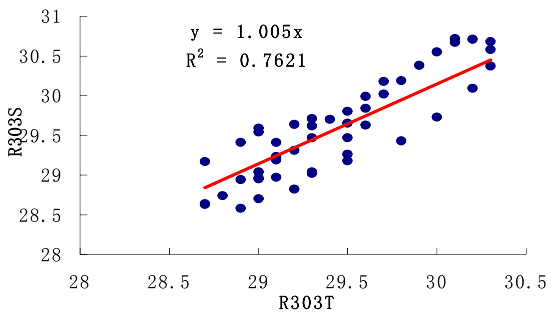

Fig. 8 the stimulant and measure temperature of R303 in caseⅢ

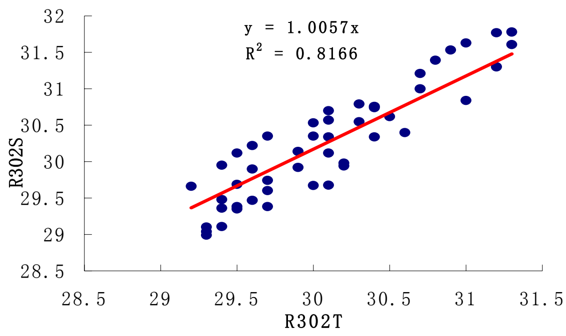

Fig. 9 the stimulant and measure temperature of R302 in case Ⅲ

Table.2 the average difference and standard deviation between stimulant and measure temperature

Case	$\Delta\Theta_{av}$/℃	$\Delta\Theta_{SD}$/℃
NO. Ⅰ R303	0.17	0.38
NO. Ⅱ R303	0.26	0.49
NO. Ⅲ R303	0.14	0.30
NO. Ⅲ R302	0.17	0.13

Seen from Fig.6 to Fig.9, the proportion of stimulant and measure temperature is all close to 1.0 and r^2 is separately 0.7725, 0.7301, 0.7621, 0.7621 and 0.8166. The above figures and table shows the agreement between the measure and the simulation is satisfactory. And the Fig.10 and Fig.11 are the temperature lines of the case Ⅲ and Ⅳ. The simulation and measure data are anastomosed.

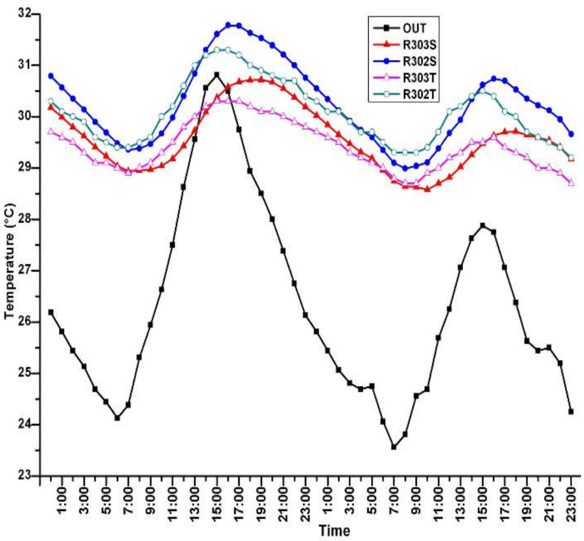

Fig.10 the measure and modeling temperature lines of case Ⅲ

OUT—outdoor temperature

R303S—the simulation data of R303

R303T—the measure data of R303

R302S—the simulation data of R302

R302T—the measure data of R302

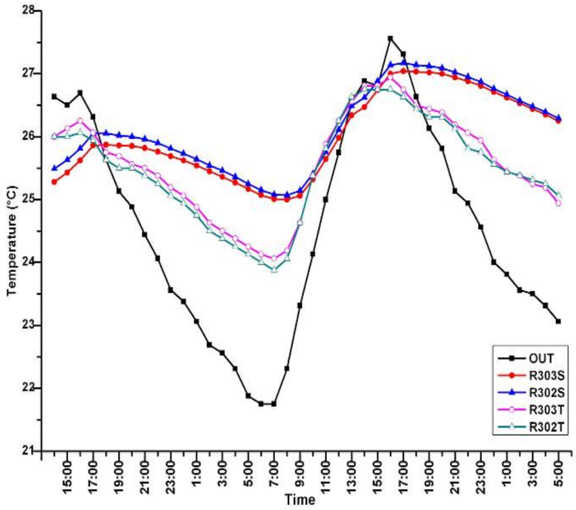

Fig.11 the measure and modeling temperature lines of case Ⅳ

OUT—outdoor temperature

R303S—the simulation data of R303

R303T—the measure data of R303

R302S—the simulation data of R302

R302T—the measure data of R302

There are only air temperature, relative humidity and solar radiation data in DeST, lacking of hourly wind direction and speed. We substitute average wind speed and dominant wind direction data from air conditioning design handbook for them. The windage need to be considered comparing to real data. When comes to natural ventilation driven by wind, this will lead to great error. So more accurate meteorological hourly data are needed.

The time steps affect the simulating results, too. The time step in DeST is 1 hour, and the coupling process in the simulation has a step with 1hour. The whole thermal process is predigested as a quasi-steady-state, in which the temperature and the spur track flux keep constant. All the above predigestions are helpful for calculation but in real situation, the temperature and the thermal flux will be invariable in 1 hour time. So we should take consideration to this effect of time steps.

Further simulation

As analysis above, the simulation and the measurement are coupling very well, and the following modeling are further study.

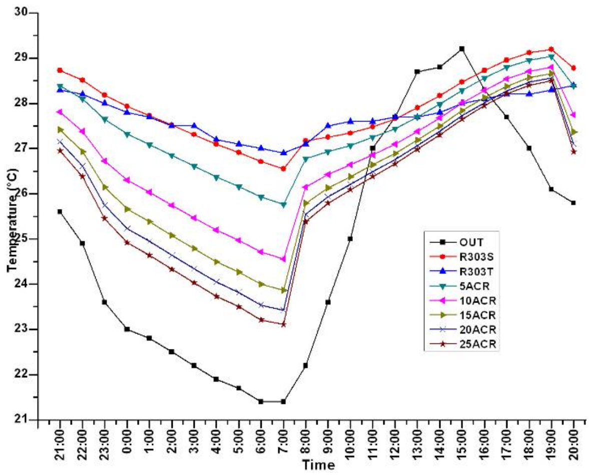

Fig.12 the simulation temperature of R303 with different air change rate

OUT—outdoor temperature

R303S—the simulation temperature of R303(3ACH)

R303—the measurement temperature of R303(3ACH)

In the Fig.12, the model is case Ⅰ, the measured solar radiation, outdoor temperature, relative humidity are input to the DeST modeling and other parameters are also from the experiment. We study different ventilation rate: 3ACH, 5ACH, 10 ACH, 15 ACH, 20 ACH, and 25 ACH. Seen from the simulation, we can learn that as the ventilation rate increases, the day time temperature decreases gradually. The temperature difference between cases 5ACH and 10 ACH is great than that between 20 ACH and 25 ACH. This shows that the temperature decrease is not simply positive proportion to ventilation. When the air change rate makes the indoor temperature closed to the outdoor temperature, there will be a little change in ventilation cooling.

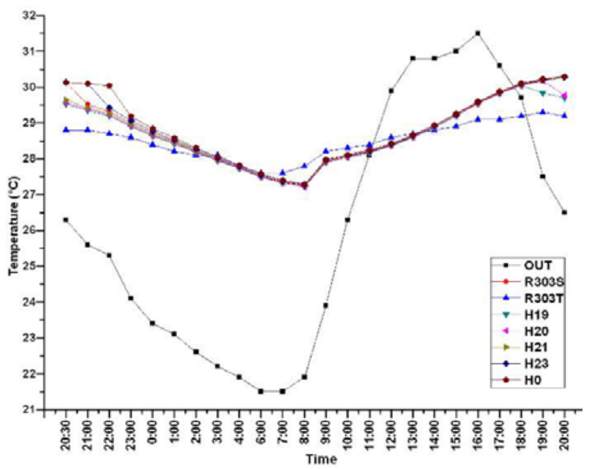

Fig.13 the simulation temperature case Ⅱ of R303 with different ventilation rate

OUT—outdoor temperature

R303S—the simulation temperature of R303 (3ACH)

R303 — the measurement temperature of R303 (3ACH)

In the Fig.13, the model is caseⅡ, the measured solar radiation, outdoor temperature, relative humidity are input to the DeST modeling and other parameters are also from the experiment. We study different ventilation time: 19:00-8:00, 20:00-8:00, 21:00-8:00, 22:00-8:00, 23:00-8:00, 0:00-8:00. Seen from the simulation, we can learn that the ventilation time affect slightly on indoor temperature. Comparing Fig.12 and Fig.13, to increase the air change rate is more useful in night ventilation cooling than to prolong the ventilation time.

Fig.14 the simulation temperature of R303 with different thermal mass in caseⅣ

OUT—outdoor temperature

0—no thermal mass

100—R303 temperature with 100 clay bricks

300—R303 temperature with300 clay bricks

600—R303 temperature with 600 clay bricks

900—R303 temperature with 900 clay bricks

In the Fig.14, the model is caseⅣ, the measured solar radiation, outdoor temperature, relative humidity are inputted to the DeST modeling and other parameters are also from the experiment. We study different thermal mass: 0,100,300,600,900 clay bricks. Because the experiment building is a light type, the increase of thermal mass can only decrease the indoor temperature in a small range. The simulation shows that for a certain building, there would be a optimal mount of thermal mass using for ventilation cooling.

CONCLUSION

Increasing the ventilation rate can improve the natural ventilation cooling effect, but it can not be a simply considered. When the ventilation rate is too high that makes the air convection strongly and quickly, it will lead to the heat convection to be the dominant heat change mode. As a result, the indoor air temperature is hardly to descend at the high ventilation rate and under heat convection. Also, it can not get a high ventilation rate in natural ventilation. So it is not feasible to increase the ventilation rate in natural ventilation.

The applicability and the effect of night ventilation is primary dependent on the minimum temperature and the daily range of outdoor. And the outdoor minimum temperature is the uppermost factor, which decides the possible minimum temperature of building envelope at the end of night ventilation. It is noticeable that the minimum temperature of building envelope is a little higher than the outdoor minimum temperature.

Whether it would increase or decrease the indoor temperature is decided by the temperature difference between indoor and outdoor. When ventilation at the lower outdoor temperature, it would lead to a decrease of the indoor air temperature, contrarily, it would hoist. As the outdoor temperature is change periodically, the building envelope temperature changes periodically with delay as the thermal inertia. In general, the outdoor temperature becomes lower than indoor temperature, so it is advised to start ventilation after this time to take use of the night ventilation cooling effect.

Night ventilation and thermal mass is an effective passive cooling strategy. It can be used integrated with other passive cooling strategies that can not only cut down the mechanical cooling energy but also improve indoor thermal comfort.

Because of the small outdoor daily range, the light office building and few thermal, it can not make the most use of night ventilation. As the experiments is taken at September and October, when it is unsteady hot and the daily range is much small than predicted, so the experimental results are not obvious. Although it is not satisfactory, we can still find that the maximum indoor air temperature is lower and the time is later than the outdoor temperature. And we can get to the conclusion that the night ventilation cooling effect is feasible for non air conditioned room in summer of Changsha.

Some perfect experimental table should be established to validation the coupling of natural ventilation model and thermal model. At the natural ventilation situation, the meteorological parameters are random, and the experimental circumstance can not be repeated, which turn into a barrier of natural ventilation. With a well-rounded experimental table, we can validation the simulation and we can further study the effecting factors of building ventilation, such as room temperature, window size, building type, wind speed and direction, etc.

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