Development of the Passive Cooling Technique in China[1]

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Abstract: With more and more energy and environmental issues, the energy-saving and sustainable development of buildings is of utmost concern to the building industry. Passive cooling techniques can optimally utilize natural resources in order to reduce the energy consumption of buildings. At the same time, it can improve the buildings' thermal environment, so that it has gained the attention of many researchers and has been applied in many different zones of China. The author summarizes various passive cooling techniques, analyzes the research methods and simulation tools, and presents the results of a survey on actual applied conditions. We put forward the pivotal factors and the development direction of the technique. Comparing the thermal comfort zone of the passive cooling technique and the mechanical types, the passive cooling technique is found to be more suitable to people.

Key words: building; passive cooling technique

1. RESEARCH BACKGROUND

Buildings, energy and the environment are key issues facing the building professions worldwide. There has been a steady increase in the use of energy in China and energy conservation is of vital importance both economically and environmentally [1]. Presently, construction industry is developing under a striking speed. In last five years, the structure built-up areas amount to 39,000,000sq.m. Along with population increasing living standard improving, the proportion of building energy-consumption to that national total energy-consumption is getting larger and larger. Concluded from statistics, there is a growing concern about energy consumption in buildings and its likely adverse impacts on the environment. It was estimated that buildings stocks accounted for 27.6% of the total national energy use in mainland China in 1998, and it is estimated that the proportion will become about 35% in 2010, even larger for the future [2]. To get comfortable thermal environment, conventional energies are used for cooling, which let the energy consumption effect more serious. One way to alleviate the ever growing demand for energy is to use passive cooling technique, which would greatly reduce energy consummation as well as improve the quality of comfort environment.

2. INTRODUCTION OF PASSIVE COOLING STRATEGIES

Passive cooling technique is to acclimate with nature principium such as sunshine, wind force, air temperature, humidity of the nature, not to resort to conventional energy consummation to the greatest extent, and in virtue of techniques such as programming, design, environments setting to improve and create comfortable living environment. Passive cooling strategies can take on the heat and humidity load of the building completely, also can be applied to take on part of heat and humidity load as supplementary when combined with other air-conditioning systems [3, 4]. Passive design methods contain optimizing solar orientation, heat insulation, best rating area of window to wall, shape, structure (heavy, less heavy and light), shading and natural ventilating of buildings, etc.

2.1 Passive cooling by thermal mass

Cooling method by making use of heat storage character of the building protection structure is suitable for climate zones that temperature difference between day and night and wind-free in most of days.

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The sun radiation intensity is heavy during daytime. To prevent outside protection structures from radiant heat of the sun during daytime, the outside surface of the heat-accumulating wall is coated with heat-reflecting boards or tint dope. During daytime the indoor thermal be absorbed by heat-accumulating wall gradually; open the heat-reflecting board outside the heat-accumulating wall, and heat-accumulating wall will cool itself down by long-wave radiation to the outside cool air at night. One of passive cooling methods used widely abroad is: considering that heat storage character of water is remarkable, the roof is regarded as a heat storage pool, and is sheltered by insulation board during daytime. Due to the cooling effect of water, indoor ceiling be cooled down, hot air upside the room be refrigerated and move down, bringing the indoor air into flow circulating. The indoor air temperature is kept within appropriate range during the daytime, when the outdoor temperature drops down at night, the insulation board be moved away, so that the pool water can absorb the indoor thermal via the ceiling, then release thermal absorbed to outside cool air at night by long-wave radiation.

2.2 Passive cooling by natural ventilation

Significance lies in two aspects if natural ventilation technique is applied: firstly since passive cooling has came into implement, that without energy consummation nature draft can cool the indoor temperature down, remove the humidity and the grime air, and improve the indoor thermal condition. Secondly it can supply fresh and clean inartificial air, which will do better to physiological and psychological health of the human's. Even in torrid regions, natural draught ventilation can be used to gain indoor thermal comfort in period time within the whole year. Especially in heavy humidity conditions, natural draught ventilation is very efficient method to gain thermal comfort. By introducing natural wind indoor during daytime and heightening the indoor air speed, natural draught ventilation can increase sweat evaporation rate from human skin, decrease the uncomfortable feeling caused by skin humidification, and enhance the convection between human beings and surrounding airs to let the temperature down. Ventilating by keeping windows open at night can remove the radiant heat accumulated during daylight by indoor building components and furniture.

1) Wind pressure ventilation

When the wind blows towards the building, owing to be obstructed by the building, positive pressure is produced along windward side of the building. At the same time, the air current move around side faces and rear of the building, negative pressure will be landed at relevant positions. Plenum ventilation is the air circulating droved by the pressure drop between the windward side and leeward side of the building. When the supply air outlet is located between the windward side and leeward side of the building, wind will flow into the room depending on the pressure drop between the positive pressure and negative pressure, thus plenum ventilation is also called 'cross ventilation'.

The effect of plenum ventilation relies on opening size and locations of wind inlets and outlets, wind speed outside, and included angle between wind direction and wind opening. To enhance ventilation effectiveness, we must organize the cross ventilation, so that the wind can move in straightway across the entire room, thus both air-inlets and air-outlets shall be set for the room. Generally speaking, the direction of cross ventilation airflow depends on the location (height, centering and etc.) and shape（normally openings，center-revolving, shutters and etc.）of air-inlets. The airflow speed depends on the area rating of extraction grille to air-inlet, supposing that air-inlet area is invariable, the larger the area of extraction grille, the higher the indoor airflow speed will be, and when the in-let opening on the positive pressure side is vertical with the leading wind, the larger the in-let opening, the larger the volume of ventilation will be. The included angle between air-inlet openings and wind direction should be designed within the range of 40 degree, if it goes beyond that, positive pressure and negative pressure zones can be created by adding air deflectors to organize the cross ventilation[5]. Brick sunk fence, wood block, fiberboard, even fabric bags can be used to guide the wind as well as organize the airflow. Window sashes can also be used to guide the wind, when the wind blow from the left wall, close the left window sash and open the right one; and vice versa. To strengthen the indoor natural ventilation, other than doors and windows, measures such as grille fan windows, fan holes among walls, ventilator scoops under the eave, ventilator fastigium and etc, can also contribute to ventilation and cooling to some extent.

2) Thermal pressure ventilation

Under the condition that outdoor wind is under a high speed as well as outdoor temperature is lower than that of the indoor, wind pressure ventilation is most efficient cooling way. In despite of that, since outdoor wind speed varies a lot, as well as the building shelters from other tall buildings and vegetation, the wind speed is not high enough to apply wind pressure ventilation, then thermal pressure ventilation would be taken into consideration. According to the theory that hot air raises, the smeary hot air can be discharged from the top extraction grilles, and fresh cool air will be sucked from the bottom of the building. The superiority of thermal pressure ventilation lies in that it is independent of the outdoor wind speed when compared with wind pressure ventilation. The effect of thermal pressure ventilation depends on the height difference between the air-inlet and the air-outlet, wind pressure intensity, and temperature difference between indoor and outdoor. The more the height difference between the air-inlet and the air-outlet, the higher the indoor airflow speed and the better the effect of convection will be; the more the temperature difference between indoor and outdoor, the more remarkable the effect of thermal pressure ventilation will be. In construction design, the vertical vacuum that run through multi-floor inside the building, such as stair wells, cortiles, air-shafts, can be used with apertures adjustable that are on top of the building, to exhaust hot air on each floor of the building, and let natural ventilation come into effect. Different from wind pressure ventilation, thermal pressure ventilation is more seasoned with changeful and execrable wind outside.

To increase height difference between the air inlet and outlet, the most efficient method is applying ventilation chimney on the roof of the building. The work principle of the chimney is: the chimney outside surface being coated by saturated pigment or protection material, if exposed to the irradiation of the sun in summer, the chimney turns hot on the outside surface; at the same time air inside the chimney is heated, rise since the air density gets light, and escape outside from the chimney top. Simultaneously negative pressure forms around air inlets located at the bottom of the room, and outdoor cool air is sucked in, so continuous airflow circulation comes into effect. To accelerate indoor airflow by setting chimneys so that ventilation run swimmingly is what called ‘Stack Effect’. According to plan arrangement and room orientations of each building, the chimney should be located at different positions. Under the condition that the floor height and height difference between the air inlet and outlet are not enough, or the condition that the room entering length is quite long, the chimney should be set on the sunward side of the building, to actualize stack-draft driven by irradiation of the sun on the chimney surface. When trees or great water area exist around air inlet side of the building, the air temperature decreased by transpiration of plant leaves or water surface before sucked into the inlet, each will do better to temperature drop. When the span of the building is quite long or cortiles being set, sufficient lighting is in demand, so we can apply lighting sunshade assisted by stack-draft chimney, which is always arranged below cortile of the building. Under arrangement like this, indoor air around the ceiling will be heated due to irradiation of the sun, and then escape outside from the top extraction grille, so negative pressure will be formed near the air inlet on peripheral walls of the building that outdoor cool air will be sucked inside and finally cooling comes true.

As supplement measure to wind pressure ventilation, thermal pressure ventilation balances the deficiency due to wind-free climate of most time in hot-summer-cold-winter climate zones. In practice, we can combine thermal pressure ventilation and wind pressure ventilation in construction design.

3) Natural ventilation by combining wind pressure ventilation with thermal pressure ventilation

As to natural ventilation design of constructions, wind pressure ventilation and thermal pressure ventilation are usually compatible with each other as supplement and dependent on each other. Generally speaking, wind pressure ventilation is used for spaces of short entering length inside the building, and thermal pressure ventilation is used for spaces of long entering length. A excellence example is the Queen's Embassy in Montfort University, Leicester, England. Two architects Short and Ford divide the huge building into a series of small blocks, which are suited to the archaic square in scale and bear a rhythm sense, meanwhile the blocks are so small in scale as to apply natural ventilation. Laboratories, offices that are of short entering length located on finger-like segments can introduce wind pressure ventilation, meanwhile report offices, halls and other rooms can actualize natural ventilation by using 'stack effect '.

4) Mechanical supplemented natural ventilation

In some large-scale buildings, the ventilation route is so long, as well as the flow resistance is so large, that simply relying on natural wind pressure and thermal pressure is not enough to drive natural ventilation. For cities in heavy air pollution and noise pollution, straight natural ventilation may take outdoor air and noise inside, which will do harm to human health. Under this condition, mechanical supplemented natural ventilation system is chosen normally. This system contains an integrated air routeway; being supplemented with air-handling measures (such as ground precool and preheat, deep well water exchange, etc.) in accordance with zoology theory, and in virtue of mechanical means so that the indoor ventilation is accelerated.

2.3 Passive cooling by night ventilation

In some regions of China, the outdoor temperature in the daytime is high, while in the evening lower than that in the daytime. What is more, in some regions, by making use of natural daily range, we can increase the ventilation volume in the evening; and use the cold accumulated by the construction protection structure in the evening to fulfill the cooling supply in the daytime. Due to thermal inertia of the building itself, night ventilation works as: after the outdoor cool air been introduced inside in the evening, by contact heat exchange between the cool air and the building protection structure which is regarded as cold accumulation material, the construction material is cooled so as to realize cold accumulation; by heat exchange between the indoor air and the construction material in the daytime, the cold stored by the construction material release to the room so as to restrain the indoor air temperature from rising. You can see this method mainly contains two processes of cold storage in the evening and cold discharge in the daytime, which of each happens at different period of time. Not only that the night ventilation bears all the virtues of passive cooling, but also settles indoor environment problems due to abundance air exchange. As for buildings that indoor heat gain is little(15～20 W/m^2), night ventilation can be applied to fulfill the human comfort demand. Multiple systems combined with night ventilation and other techniques can be applied in business constructions as well as civil constructions: combining night ventilation with evaporative cooling techniques such as roof evaporative cooling systems, driven by fans in the evening, the outdoor wind will be precooled by indirect evaporative cooling, also can cool the supply air and increase cold storage of the building as well, when applied in civil constructions can replace conventional cooling completely; combining night ventilation with phase-change cold accumulation, cooling accumulated from night ventilation as well as making use of potential heat can take on the full or part of cooling load in the daytime[6].

2.4 Passive cooling by evaporative cooling

Evaporative cooling is a cooling method through heat and humidity exchange between water and air. The water being kept in direct contact with the air, the water will absorb heat during the evaporation process and exchange heat and humidity with the air without enthalpy change, resulting that temperature of both the water and the air drop, as well as that and humidity content of the air increase. Method utilizing the air mentioned which is wet and cool is called direct evaporative cooling (DEC); and that utilizing the above air to cool water medium, then using the water medium to cool the indoor air is called indirect evaporative cooling (IEC). In dry and less dry regions, evaporative cooling techniques can be applied to fulfill the indoor comfort completely; even can be applied in wet regions to some extent [7].

2.5 Passive cooling by radiation cooling

Over here it refers to heat radiation and cooling of the building protection structures by themselves according to long-wave radiation heat transfer of the structure surface. The temperature of the astrospace is close to absolute zero, and that of outside atmosphere is quite low too, therefore as to buildings located on the earth's surface, the sky is a natural huge refrigeratory. On the other hand, due to the existence of vapour, carbon dioxide, and ozone, the aerosphere transmissivity to different electromagnetic waves varies, wavelength band of strong transmissivity is called 'atmospheric window'. Aerosphere contains many atmospheric windows, the wavelength band whose wavelength is within 8～13μm is of interest, since black body radiation energy under normal temperature is mainly contained in this band. In the evening, the radiation power from atmospheric windows to the building is limited, and that the building's energy radiate to the sky through atmospheric windows of 8～13μm wavelength is more, so as to natural cooling of the building actualize. As a result of the two processes will come into homeostasis finally, the cooling capacity and the gained lowest cooling temperature of this natural cooling method are limited. To apply selective spectrum radiation material can strengthen the effect of radiation cooling. The period of radiation cooling research is not quite long, and more ideal selective spectrum radiation material is still in search, but the significance of passive cooling by radiation cooling adapted in constructions is remarkable: as to the building free of air-conditions, it is useful for cooling to some extent; and to that having applied air-conditions it can be used to lower the cooling load. Concluded from literature reports, the cooling capacity per area can amount to 40～50W/ m^2, and the temperature difference can reach about 15℃ [8].

3. MAIN RESEARCH METHODS OF PASSIVE COOLING TECHNIQUE

From basic research to practical application, some research work on passive cooling technique has practised into maturation and systematism, multiplicate software can be introduced for calculation and energy-consuming assessment in construction design.

Main research methods include:

3.1 Microcosmic description model

Namely CFD. Natural ventilation simulation in universal CFD software generally does not take heat conduction and storage of the wall into account, but is limited to calculation of liquid velocity field and temperature distribution under certain thermal boundary conditions, such as analysis of natural ventilation coated with heat preservation protection structure. CFD model needs to divide grids, also named microcosmic method [9].

CFD is a method applied extensively, which is carried out by doing simulative experiment on the computer, dividing the room into small blocks within control, and dispersing sequential differential equations controlling the airflow by finite-difference or finite element method, combining practical boundary conditions to find answer for the above algebra equations on the computer. As long as the blocks divided are small enough, discrete values in discrete areas can be considered as representation for air distribution state of the entire room. The blocks divided can be so small that they can be applied to describe the flow field at length. But the issue under solution is non-linear, needs to be iterated repetitively; therefore it is a bit time-consuming. It can be coupled with construction energy simulation software such as EnergyPlus. CFD can not simulate the airflow of the entire building, nor set up boundary conditions, so it is seldom used as a ventilation design tool [10].

3.2 Macroscopical analysis

Macroscopical description model ideally takes the building system for a series of control blocks, can be mathematically described by algebra method or common difference method. For common algebra equations, we can find the mathematics key directly, and analyse results from qualitative analysis and quantitative analysis of parameter influence factors. For higher order equations and coupled nonlinear equations, we can disperse equations, so that find calculation results under certain conditions. Compared with CFD simulation methods, macroscopical analysis can do analysis of certain factor influence variety rules more easily, but the disadvantage lies that it can not predict airflow distribution in detail nor predict parameter distribution.

Analysis tools used commonly for passive cooling technique include: building natural ventilation analysis tool：BREEZE，COMIS，AIRNET and etc, which can apply quasi-static-state method to simulate the situation under all-year climate conditions, can be used to predict the ventilation capacity and optimize design means, but they are only available for conditions that under heat preservation, that do not take the construction heat conduction process into account [11].

Structure thermal process analysis program: BLAST，developed by Illinois university, has been applied by Kammerud to study nighttime ventilation cooling effect in different regions of America, but the building interior natural ventilation model and convection heat exchanger index are still within limits.

NatVent: The NatVent programme is made to serve as a pre-design tool that can be used early in the design process before explicit data about the building and the ventilation system is known. Therefore assumptions and simplifications about the building and the ventilation system are made within the programme [12].

ESP-r: ESP-r is flexible and powerful enough to simulate many innovative or leading edge technologies including daylight utilisation, natural ventilation, combined heat and electrical power generation and photovoltaic facades, CFD, multi-gridding, and control systems.

ECOTECT: Complete environmental design tool which couples an intuitive 3D modelling interface with extensive solar, thermal, lighting, acoustic and cost analysis functions. ECOTECT is one of the few tools in which performance analysis is simple, accurate and most importantly, visually responsive. Allows the user to "play" with design ideas at the conceptual stages, providing essential analysis feedback from even the simplest sketch model. ECOTECT progressively guides the user as more detailed design information becomes available. As the program can perform many different types of analysis, the user needs to be aware of the different modelling and data requirements before diving in and modelling/importing geometry. For example; for thermal analysis, weather data and modelling geometry in an appropriate manner is important; and appropriate/comprehensive material data is required for almost all other types of analysis.

4. THE ANALYSIS OF POTENTIAL USE OF PASSIVE COOLING STRATEGIES IN CHINA

The effect of passive cooling technique is associate with the climatic condition, and the potential use of passive cooling design strategies is variational with the different regions. In China, there are, broadly speaking, five climatic types, namely severe cold, cold, hot summer and cold winter, mild and hot summer and warm winter [13].

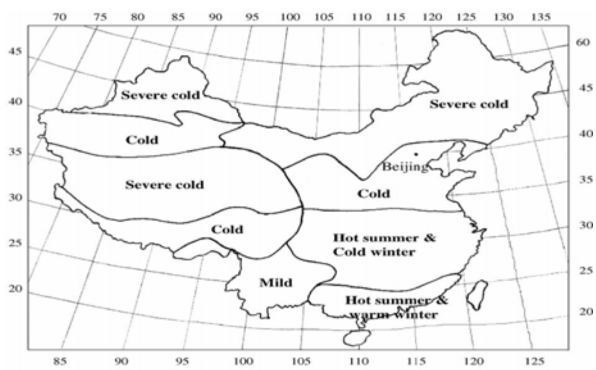

Fig.1 The five major climates in nine geographical regions based on Ref.[13].

Table 1 shows a summary of the potential use of passive design strategies for the 18 cities in China during the six-month warmer half of the year[14]. In general, no air conditioning would be required if proper passive cooling techniques such as natural ventilation, thermal mass or evaporative cooling are adopted. In the hot summer climate zone, passive cooling techniques range from 47% to 61% during the summer months. Periods requiring air conditioning vary within 10-18%. Potential use of passive cooling techniques ranges from 50% to 64% during the warmer half of the year, and 25-50% of the time air conditioning would be required for thermal comfort.

Tab.1 Summary of potential use of passive design strategies for the 18 cities during the warmer half of the year[14].(April–September)

City	1 %	2 %	3 %	4 %	5 %	6 %
Altay	1	0	1	0	0	0
Urumqi	8	0	8	0	0	0
Huhhot	2	0	2	0	0	0
Changchun	28	28	0	0	0	0
Shenyang	30	30	0	0	0	0
Turpan	50	0	43	7	50 (d)	0
Beijing	40	35	5	0	0	0
Xi’an	45	37	6	0	0	2
Lhasa	0	0	0	0	0	0
Nanjing	57	47	0	0	0	10
Shanghai	58	48	0	0	0	10
Chengdu	54	54	0	0	0	0
Wuhan	76	61	0	0	0	15
Nanchang	79	61	0	0	0	18
Kunming	6	6	0	0	0	0
Guangzhou	86	61	0	0	0	25
Nanning	94	64	0	0	0	30
Haikou	100	50	0	0	0	50

1. Cooling requirement (a)
2. Natural ventilation (b)
3. Thermal mass (b)
4. Thermal mass with night ventilation (b)
5. Evaporative cooling (b)
6. Air-conditioning (c)

a. Cooling requirement during the six-month warmer half of the year.

b. Percentage of the time that passive cooling technique may be effective during the six-month warmer half of the year.

c. Percentage of the time air-conditioning would be required during the six-month warmer half of the year.

d. Alternative passive design strategy.

5. PROGRESS IN THE RESEARCH ON PASSIVE COOLING TECHNIQUES

5.1 Domestic research advances

The research on the passive architecture design has progressed greatly in China. Recently, since the Green Buildings and Sustainable Development has become established, people in related field pay more and more attentions on the ecological construction design theory concerning local characteristics and utilizing natural climate resources. On experiential scientific research of ordinary residential ecological construction, considering that the Mountain Climate and basic local residential conditions in south of Shanxi, experts such as Liu Jiaping advocate new type compacted ecological house, which make full use of the design tenet: passive design, heat and moisture preservation of ecological protective structure combined with natural ventilation[15]. Professor Meng Qinlin of South China University of Technology proposed that to lay moist porous media on the building roof surface, to make up water evaporated in the layer by natural precipitation, to consume the sun radiation thermal by water evaporation in the layer, so that preventing the roof surface from being heated to aim at cooling and energy saving; when the temperature drop of the building roof surface reaches 25℃, that of roof interior surface will lead to 5℃, the performance is more excellent than that of traditional roof pond. Professor Jiang yi of Tsinghua University advanced theories and measures of green residence design [16], research trends of phase change wall and evaporative cooling technique, after systemic research on the micro-weather environment in city residences from layout and construction of indoor and outdoor physics environment and environment regulating system. As the aspect of natural ventilation simulative model, based on aperture theory of hydrostatics, scholar Li Guoji in Hongkong practiced systemic theory analysis and investigation of various natural ventilation for the unsheltered building with two small air intakes(the height of air intake is small compared with that of the room) [17,18].

5.2 Overseas research advances

Passive cooling techniques is popular in overall Europe, while in the Mediterranean the natural ventilation method is architects and designers most favorable choice for the purpose of reducing the building cooling load and improving the indoor comfort, since the air-conditioning is not a systematic and practical way in this area[19,20]. It is a pity, however, that natural ventilation strategies integrated as a compatible passive cooling in the construction design is still under development. To make up the existing defect, the research team consisting of Belgium, France, Greece, Italy, Portugal, Spain and Swaziland in cooperation have made great progress in the aspect as natural ventilation of the passive cooling subject [21, 22]. Based on a mass of experiments, various aspects are involved in the passive cooling research: single side ventilation, cross ventilation, the airflow of at-vent, and the night ventilation coupled with thermal mass. More than 100 experiments on single side ventilation and cross ventilation inside buildings and labs are carried out by many countries in Europe. All results of ventilation research are accumulated in “Ventilation--Sub-project of Thermal Mass Research Report”. The research period of radiation cooling is not enough. Scientist of Italy, Canada, Australia, and etc have carried out experiments on buildings, and the achievement is satisfying. While scientist of Japan, Sweden has achieved a breakthrough in the item of radiation material.

6. CONCLUSIONS

As more and more attention is paid on the building energy conservation, healthy building and indoor and outdoor environment sustainable development, the passive cooling method becomes an important and urgent strategy in hot summer area. We can improve effectively the indoor thermal environment, meet the ventilation requirement and satisfy the mental natural tendency through passive cooling strategies like natural ventilation which are according with the prevailing healthy, comfortable and ecology human habitat environment development. And for the research on passive cooling strategies, the regional climate analysis is very important. We should notice the advantages of passive cooling, also its limitations. Both the effective application of passive cooling methods and the reasonable application methods of equipments cool are helpful for the improvement of the indoor thermal environment and the comfort in summer and reduce the energy consumption.

The key research problems:

1) At the pre-design, the quantitative analysis about the site climate conditions is needed. The thermal environment affecting factors in summer should studied and bring forward viable passive cooling design method and specific application technical measures combined the practice.

2) Analysis on the thermal environment affecting factors in summer functions should be done quantitatively. For the different passive cooling strategy, the space thermal comfort characteristics are not the same; the effect can be got from quantitative analysis, which is help for the design purpose of the improvement.

3) The application of building thermal mass for energy storage to reduce heating/cooling load is widely concerned by building service engineers. Thermal mass and its applications have long been studied in the literature. The future work we need to identify an ideal building model that allows a theoretical study of the effect of thermal mass. The main focus is to study theoretically and numerically the non-linear coupling between ventilation and internal thermal mass in naturally ventilated buildings.

4) Thermal environment dynamic analysis model and computational tools suitable for natural ventilation in the residential building are another work. Quantitative analysis can avoid the fuzzy or wrong design; can lead to correct, scientific evaluation on thermal environment in the natural ventilation space. And the key problem is the nonlinear coupling of natural ventilation rate and building thermal environment.

The good cooperation between the designer and engineer is required for the building environment research, which is also the continuing work and development direction. Further work is still required to make full use of these passive cooling in building designs.

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