Review of energy saving technologies research in HVAC systems

Yonghao Pan*

Southwest Jiaotong University, Chengdu, China.

Abstract. Energy consumption in the building industry occupies a significant portion of the world's total energy consumption, and heating, ventilation and air conditioning (HVAC) systems are one of the largest energy consumers in buildings. Therefore, research on energy-saving technologies and measures for HVAC systems is essential. This paper first analyzes the workflow of HVAC systems and the causes of energy consumption, followed by combing and summarizing the existing research on energy-saving technologies for HVAC systems, namely passive energy-saving technologies, active energy-saving technologies and intelligent energy-saving technologies. In order to better understand and apply aforementioned energy-saving technologies, this paper takes a science and technology building built 30 years ago in southwest China as an example and applies the relevant energy-saving technologies to upgrade the HVAC system in a targeted manner.

Keywords: HVAC; energy saving technology; building energy consumption; energy saving and emission reduction.

1. Introduction

In 2021 the International Energy Agency released *Net Zero by 2050: a Roadmap for the Global Energy Sector*, which aims to provide guidance for the global energy sector to achieve the Net Zero goal by 2050 [1]. However, since the release of the report, the world energy crisis has worsened, and according to *Statistical Review of World Energy*, the global energy system in 2022 faces the greatest challenges and uncertainties in nearly 50 years[2]. Therefore about energy saving and green low carbon is a major challenge that needs to be addressed urgently. Energy consumption in the building sector accounts for a significant portion of the world's energy consumption, with surveys showing that building operations account for 30% of global energy consumption and 27% of total energy sector emissions in 2021, with both energy consumption and emissions rebounding to above 2019 levels in 2020 following a decline due to the new crown pneumonia restrictions [3].Therefore, the building industry, which is a major energy user, needs to promote changes related to energy efficiency and emission reduction in order to achieve the goal of having all new buildings and 20% of existing buildings achieve zero carbon emissions by 2030 and net zero emissions by 2050. Among the huge building energy consumption, heating, ventilation and air conditioning (HVAC) systems are among the largest energy consumers in buildings. The energy use of HVAC systems has grown significantly with the increased reliance on HVAC systems in residential, commercial and industrial environments[4]. Since 2000, energy use for cooling buildings has doubled due to rising temperatures and increased human activity, making it the fastest growing segment of building energy use. In particular, space cooling demand increases by more than 6.5% in 2021 compared to 2020 [5]. However, there are still many problems with the HVAC design of construction projects, the design concept of energy saving and emission reduction is not fully integrated into the construction project, and the energy saving technology of HVAC system needs to be more intelligent and systematic in order to greatly reduce the energy consumption problem of HVAC system.

HVAC system energy saving technology is an important part of promoting the building industry to reduce energy consumption. With the popularization of HVAC systems in engineering, there have been many more mature and energy-saving systems that have come into play, among which the more widely used systems are high-efficiency server room full conversion systems, heat recovery systems, natural cooling systems, heat pump systems, ice storage and cooling air conditioning systems [5]. However, the energy-saving effect of these systems is still not very satisfactory, so a large number of researchers are engaged in research on HVAC energy-saving related technologies, the use of renewable energy, variable frequency technology, air heat recovery technology and natural ventilation technology, and have proposed many advanced and effective HVAC system skills and measures [6–12]. In addition, with the development of computer

* Corresponding author: PanYonghao@my.swjtu.edu.cn

technology, intelligent technology has injected new impetus into the research of HVAC energy-saving technology. Refined design of HVAC energy-saving technology, scientific use of frequency conversion equipment, intelligent control and detection systems, building automatic control systems, and AI energy-saving control technology are continuously developing [13–15]. This paper summarizes the research progress of HVAC system energy saving technology, classifies and sorts out the current energy saving technology about HVAC system, and combines some of the technologies in the paper with the actual project based on an engineering case to verify the effect of relevant HVAC system energy saving technology in energy saving and emission reduction, the main content of the article is shown in Fig. 1.

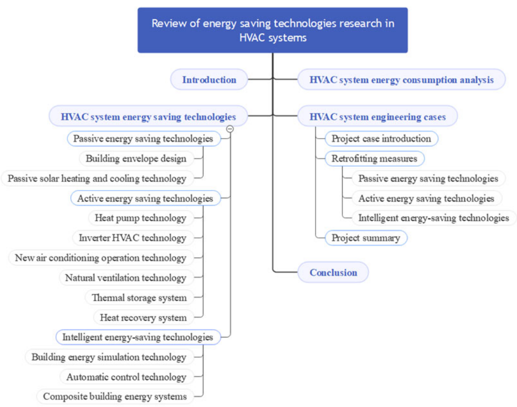

Fig. 1 Main content of the article

2. HVAC system energy consumption analysis

The central air conditioning system is generally composed of cold and heat sources, transmission and distribution systems, air handling equipment and end devices, cold and heat sources are used to provide the energy required for cooling or heating, that is, we often say the host (outdoor unit), the transmission and distribution system is the cold and hot water/wind generated by the cold and heat sources to the required place, that is, we often say the air duct system/water pipe system, Air handling equipment is used to produce the required air, such as air conditioning boxes, fresh air units, air handling units and other equipment, the end equipment is the last link to send cold and heat into the room, including radiators, various types of air supply outlets, fan coils, floor radiation heating/cooling. Ideally, the selection and deployment of energy-efficient technologies in buildings needs to be coordinated with several other components or elements of the infrastructure, so that achieving zero carbon emissions requires coordination between building strategies and infrastructure development.
The energy consumption of air conditioning refrigeration units cannot be ignored. The length of the operating time of the refrigeration unit, the load rate of the refrigeration unit and the rated power have a certain impact on its energy consumption.
The energy consumption of the conveying system is relatively large. 60% to 70% of the building's large heating power consumption is consumed by fans and pumps that distribute and transport heat and cold[16].
The energy consumption of an air conditioning end unit is closely related to its end form. The load in the room is variable and can be changed simultaneously by adjusting the end units. If the room temperature is always maintained at a lower value, it will increase energy consumption.
The construction quality of the water system circulation in HVAC also significantly affects the energy consumption of the HVAC system, because the smoothness of the water circulation has a great impact on the consumption of the HVAC system, and ensuring that this part of the construction process has sufficient safety and stability can guarantee the overall quality of the system.

3. HVAC system energy saving technologies

This section introduces the energy-saving technology of HVAC system into three parts: passive energy-saving technology, active energy-saving technology and intelligent energy-saving technology. Passive energy saving technology refers to the technology that does not use mechanical and electrical equipment to achieve energy saving in buildings. Active energy saving technology refers to the technology that provides comfortable and energy saving environmental control for buildings by using mechanical equipment, optimizing equipment systems and equipment selection. Intelligent energy-saving technology refers to the technology that realizes energy saving with the support of computer network, big data, Internet of Things, artificial intelligence and other technologies.

3.1 Passive energy saving technologies

3.1.1 Building envelope design

The enclosure, as the boundary between the building and the outdoor environment, has a relatively large impact on the temperature regulation and energy efficiency of the building. Many researchers have studied the improvement of building envelope, the impact of building envelope on building energy consumption[17]. In addition, the use of vegetation has become an important strategy in today's urban planning, and building envelope greening is an obvious choice to meet greening requirements in densely built urban centers. Building greenery has many ecological advantages, including increased insulation of the building envelope and reduced urban heat island effect, buffering of rainwater, improved air quality and increased carbon dioxide absorption, among other advantages [18–20]. Building envelope greening can improve the building's insulation capacity and heat transfer parameters, which can ensure that when the outdoor temperature changes, the indoor temperature fluctuation is maintained in the smallest possible range, so that it better meets the needs of human comfort[21,22].As can be seen above, the design of the building envelope has a significant impact on building energy consumption, and is also essential to ensure indoor environmental quality, comfort and safety.

3.1.2 Passive solar heating and cooling technology

Passive solar buildings are environmentally friendly buildings designed to create a comfortable indoor environment that uses the radiant heat of the sun to provide heating for the building in the winter and lower the indoor temperature in the summer. Passive solar houses are unique in using the structure of the house itself to collect solar energy, and have excellent heat storage performance, which can maintain a stable temperature for a certain period of time. While there is a certain initial cost to pay, the payoff is long-term energy savings[23,24]. In addition, the intermittency and low density of solar energy will greatly limit the application of solar heating. In response to this problem, some studies have begun to combine heat pump technology with solar heating technology to develop solar-assisted heat pump heating system to solve this problem[25]. Passive solar energy system is relatively full of energy utilization, high efficiency, economical and simple and easy to operate, and has a broad development prospect[26,27].

3.2 Active energy saving technologies

Heat pump technology

Nowadays, more and more countries have recognized that heat pump technology is a key technology for thermal decarbonization, and more policy support has been provided in recent years[5]. As long as the appropriate low-grade heat source is selected, the heat pump can efficiently convert electricity to heat, which is a very important path to achieve zero-carbon energy in the future[7]. However, only about 10% of building heating demand is met by heat pump technology, and policy support and technological innovation are needed to further develop heat pump technology by reducing upfront procurement and installation costs and improving energy efficiency[5].

3.2.1 Inverter HVAC technology

In HVAC system, frequency conversion and fixed frequency are two main design methods. Among them, frequency conversion design is more widely used in HVAC system, and its energy saving effect is better. Frequency conversion HVAC mainly uses frequency conversion speed regulation technology to reduce the energy consumption of HVAC equipment. When the HVAC load in the building has a significant change, the HVAC energy consumption can be reduced by fans, water pumps and chiller facilities, so that the HVAC can meet the relevant energy saving standards in the operation state. By using frequency conversion technology, the energy saving effect of HVAC can be promoted to 30%[8]. In addition, frequency conversion technology has low maintenance costs and long service life, which can further reduce the total initial investment.

3.2.2 New air conditioning operation technology

The new air conditioning operation mode refers to the use of different combinations of environmental parameters to produce different thermal comfort effects. For example, during the winter, when the indoor temperature is raised using traditional air conditioning methods, heat and moisture are exchanged between the human body and the environment through the air, which requires higher air humidity. In this case, however, both the heat loss from the fresh air being heated and the heat loss from servicing the structure are relatively large. If we can apply new thermal and humid environment applications, optimize the choice of air conditioning operation mode and increase radiant heat, we can significantly reduce air humidity[28].

3.2.3 Natural ventilation technology

Natural ventilation technology has the characteristics of reducing energy consumption and improving indoor environment, and has become an important solution for the sustainable development of the construction industry[10,11]. The use of indoor and outdoor air exchange, can reduce the room temperature and exhaust moisture, to ensure the normal climate conditions of the room and clean air, at the same time, there is a certain air flow in the room, can strengthen the body's convection and evaporative heat dissipation, improve the body's thermal comfort feeling, improve people's working and living conditions, has been widely used.[29–31]. In addition, mixed-mode ventilation has been shown to be an effective energy-saving technique for buildings designed using NV principles[32]. At present, the measurement of natural ventilation effect is mainly determined by the number of air changes and air flow organization. With the development of computer technology, computer simulation has become a very important method to calculate the effect of natural ventilation. Research on the potential of natural ventilation technologies from around the world provides valuable guidance to architects and policymakers worldwide for the effective use of NV designs that meet local climatic conditions[11,33–35].

3.2.4 Thermal storage system

Thermal storage system(TSS) is a kind of technology which can store cold when the power grid is low and release the cold storage capacity when the air conditioning load is peak, and has been widely used[12]. The filling temperature of the chilled water storage tank is generally 4 ° C to 6 ° C. All chilled water storage systems reduce peak cooling demand by 80 to 90 percent compared to conventional refrigeration systems[9]. The research shows that although the heat storage system can not necessarily save energy, it can significantly reduce the energy cost. For example, an all-ice heat storage system can save up to 55% on monthly cooling electricity bills, even though it only reduces system energy consumption by 5%[36].

3.2.5 Heat recovery system

Heat recovery technology can recover and use the waste heat generated during the operation of air conditioning units, as well as the heat in the air. Heat recovery technology can use the heat energy exchange between fluids to achieve building energy saving and reduce costs. These systems can be divided into two main categories, one is the recovery of sensible heat systems, and the other is the recovery of enthalpy heat systems[6]. The heat recovery system is generally installed on the roof and consists of a core unit, pipes and blowers. Current heat recovery systems can recover about 60 to 95 percent of the heat[37], which is already very efficient. The air conditioning heat recovery system can make full use of the waste heat of the air conditioning system effectively utilize the low-grade heat energy, and realize the role of energy saving.

3.3 Intelligent energy-saving technologies

3.3.1 Building energy simulation technology

Building energy simulation programs are efficient and convenient for assessing energy performance over the life cycle of a building during the design and operation phases of a building. Building energy simulation programs have continued to evolve and advance over the past 50 years. The first generation of building energy simulation software was developed based on analytical equations found in design manuals. The second generation is based on simplified dynamic model; The third generation adopts the numerical calculation method, which can realize the partial integration of the thermal performance of the building such as sound, light and heat. The fourth generation fully integrated the simulation functions of sound, light, heat and other aspects of the building[38]. From the first generation to the fourth generation, the simulation results are gradually close to the actual situation of building energy consumption, but at the same time, it is more complex to use, and in terms of professional aspects, the software users also put forward higher requirements. Building energy modeling can help building design better meet the needs of society without wasting excess resources. Therefore, in building design and construction projects, accurate prediction of building energy efficiency is very important[14,39].

3.3.2 Automatic control technology

The automatic control of HVAC system is an effective way to save resources. With the rapid development of high-tech information technology and computer network technology, the requirements for the optimal combination of building structure, system, service and management are getting higher and higher. Intelligent building control system is born in accordance with this trend. The effective implementation of energy-saving automatic control can minimize the consumption of electric energy and improve the efficiency of heat storage and resource utilization[40]. Building automation technology can achieve comprehensive monitoring and management of buildings through the integration of various sensors, controllers and software systems, thereby improving the energy efficiency, safety and comfort of buildings. At present, intelligent buildings have become the trend of the development of world architecture, which can not only promote the function of buildings, but also provide a stable and convenient living and working environment for the public.

3.3.3 Composite building energy systems

The composite building energy system is a system that comprehensively considers the matching and management of building energy system, which has more advantages than sustainable buildings. The composite energy building energy supply system combines various forms of energy together to enhance the diversity of energy use. In the system, energy is saved through mass flow or energy flow information sharing, and the primary energy utilization rate can reach 70-80%. The main contents include the optimal utilization of different types of energy, the integration of equipment and the development of complex theories[13]. Complex building energy system is a system engineering involving multiple disciplines, which is still in the development stage and needs more research.

4. HVAC system engineering cases

4.1 Project case introduction

The engineering case selected in this section is a science and technology building of an engineering institute located in southwest China, which is an existing building renovation project. The science and technology building was designed in September 1985, the building has been used for 30 years, the office conditions, fire-fighting facilities, electricity facilities, communication and intelligent facilities in the building can no longer meet the needs of use, the building technical indicators and floor plans are shown in Table 1, Figure 2.

Table 1 Overview of original appearance

Total floor area	$8143.93m^2$
Engineering scale design level	Grade 2
Building fire categories	Class II high-rise office building
Building fire resistance class	Grade 2
Building height / number of floors	43.45m 10 floors above ground, 11 floors locally
Structure type	Reinforced concrete-frame shear wall
Basic form	Prefabricated square pile foundation
Structural design service life	50 years
Roof waterproofing grade	Grade 2

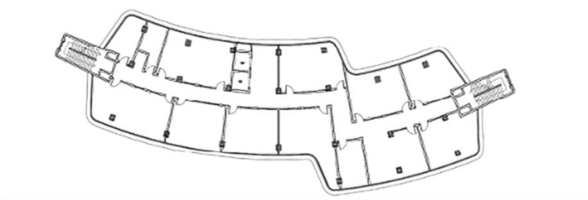

Fig. 2. Original building plan

The main problems related to HVAC of the old project are as follows:
(1) The structure type of the original building is reinforced concrete-frame shear wall, the envelope structure has no heat insulation measures, the thermal performance is poor, and the indoor comfort is not guaranteed.
(2) The split type air conditioner is used, and the outdoor unit of the split type air conditioner is distributed randomly, which affects the main façade along the street and has safety problems.
(3) The water pump is set on the first floor, and the low-frequency noise emitted has a large impact on the office workers on the lower floors.
(4) In winter, the exterior doors and windows are closed and no fresh air is supplied indoors, resulting in poor indoor environmental quality, high CO2 concentration, sleepy personnel, and affecting work quality; some offices open windows directly, resulting in increased energy consumption due to increased air conditioning load.

4.2 Retrofitting measures

4.2.1 Passive energy saving technologies

After the renovation, vertical greening was adopted. The east side of the building forms a green barrier, which improves the thermal performance of the building maintenance structure and provides a green landscape for the people inside.

Before the renovation, the building shape was permeable from north to south, and the one-line arc shape catered to the summer wind direction, which guided the wind into the interior and enhanced natural ventilation. According to the analysis of the simulation results, the average number of natural ventilation changes in the main functional indoor rooms after the renovation reached 97.82%, with a good effect of indoor natural ventilation and an obvious improvement of the indoor temperature and humidity environment.

4.2.2 Active energy saving technologies

The project's original air conditioning system was split air conditioning with a messy arrangement of outdoor units. After the renovation, the centralized split air conditioning system (air-cooled heat pump air conditioning system) was adopted, and the new air was equipped with heat recovery, CO2 concentration monitoring, photocatalytic purification and PM2.5 removal technology, which comprehensively improved the indoor air comfort and air quality.

4.2.3 *Intelligent energy-saving technologies*

The intelligent control design of the building includes intelligent control of lighting system, energy-saving control of heating and cooling, intelligent control of conference rooms, and control of access control and time and attendance.
The project also studied the relationship between the reserved part of the building and the expansion by using BIM technology, and made deeper design for external shading, windows, and part of the decoration, using pipe collision to avoid errors at the design stage, and using BIM to guide the construction on site, while realizing the operation and maintenance management at a later stage through this technology.

4.3 Project summary

The Chinese Academy of Sciences Science and Technology building renovation project adopts a series of green building technical measures such as passive building energy-saving design, roof + vertical greening, online air quality monitoring and control, rainwater recycling and utilization, building reinforcement and energy consumption and vibration reduction technology, saving 1,771 tons of standard coal and reducing carbon dioxide emissions by 4,605 tons per year. The application and combination of various HVAC system energy saving technology makes the building more energy saving and comfortable, which shows the feasibility and superiority of HVAC system energy saving technology.
This retrofit project is undoubtedly a successful and typical engineering case, but the result of the retrofit is still some distance away from a near (net) zero energy building. From a contemporary perspective, there is still some room for improvement. For example, the use of low-grade energy can be increased, and solar heat pump technology can be used in combination with solar heating technology. The material and thermal performance of the

envelope can be improved by using green building materials such as vacuum glass, eco-cement and phase change building materials. The use of thermal storage systems can be increased, shifting energy use from peak to off-peak hours to avoid peak demand charges. Advanced automatic control technologies can be used in energy saving systems, etc.

5. Conclusion

This paper mainly focuses on HVAC system energy saving technology as the main research subject, and firstly analyzes the energy consumption aspects of HVAC system with the aim of discovering the possible causes of increased energy consumption. This article introduces the research progress of HVAC energy-saving technologies from three perspectives: passive energy-saving technologies, active energy-saving technologies and intelligent technologies. The article concludes with an analysis of the HVAC technologies and green building technologies applied in a science and technology building renovation and expansion project in southwest China, built 30 years ago, in which the combination of the aforementioned HVAC system energy-saving technologies and engineering practices is realized, and the following are the main conclusions of the paper:

(1)Passive energy-saving technologies have the advantages of good energy efficiency, low technical requirements, low maintenance frequency and good economy, but their energy-saving effects are often limited. Active energy-saving technologies and intelligent energy-saving technologies generally have higher requirements for equipment and technology, large one-time investments, and consume a certain amount of energy during use, but they can meet the needs of human comfort to a greater extent and improve the energy-saving effect of buildings, and can be applied to buildings as an enhancement means of passive energy-saving technologies. Passive and active approaches in building energy efficiency design are closely linked and complementary.

(2)Although the actual project is still dominated by passive energy-saving technology and active energy-saving technology, but with the continuous development of intelligent technology, intelligent energy-saving technology is becoming more and more mature, HVAC system energy-saving measures have begun to appear toward the trend of intelligent development, intelligent skills technology development potential is huge, and there are irreplaceable advantages.

(3)Many HVAC systems in existing buildings have high energy consumption, especially buildings built long ago, so in the process of achieving energy consumption reduction in the construction industry, the renovation of HVAC systems in existing buildings is very necessary, so it is also very meaningful to study the application of relevant advanced energy-saving technologies in the renovation process of existing buildings.

References

1. Net Zero by 2050 – Analysis[EB/OL]//IEA. [2023-05-06]. https://www.iea.org/reports/net-zero-by-2050.
2. Statistical Review of World Energy | Energy economics | Home[EB/OL]//bp global. [2023-05-04]. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.
3. CO2 emissions from energy combustion and industrial processes, 1900-2021 – Charts – Data & Statistics[EB/OL]//IEA. [2023-05-06].
   https://www.iea.org/data-and-statistics/charts/co2-emissions-from-energy-combustion-and-industrial-processes-1900-2021.
4. VAKILOROAYA V, SAMALI B, FAKHAR A, et al.. A review of different strategies for HVAC energy saving[J/OL]. Energy Conversion and Management, 2014, 77: 738-754.
   https://doi.org/10.1016/j.enconman.2013.10.023.
5. Buildings – Analysis[EB/OL]//IEA. [2023-05-06]. https://www.iea.org/reports/buildings.
6. CUCE P M, RIFFAT S. A comprehensive review of heat recovery systems for building applications[J/OL]. Renewable and Sustainable Energy Reviews, 2015, 47: 665-682. https://doi.org/10.1016/j.rser.2015.03.087.
7. CHUA K J, CHOU S K, YANG W M. Advances in heat pump systems: A review[J/OL]. Applied Energy, 2010, 87(12): 3611-3624.
   https://doi.org/10.1016/j.apenergy.2010.06.014.
8. TAO R, JINGMIN G, WENWEN J. Automatic Control Technology in the HVAC System[C/OL]//2009 International Conference on Advanced Computer Control. 2009: 315-318. https://doi.org/10.1109/ICACC.2009.9.
9. HASNAIN S M, ALABBADI N M. Need for thermal-storage air-conditioning in Saudi Arabia[J/OL]. Applied Energy, 2000, 65(1): 153-164. https://doi.org/10.1016/S0306-2619(99)00107-5.
10. TONG Z, WHITLOW T H, LANDERS A, et al.. A case study of air quality above an urban roof top vegetable farm[J/OL]. Environmental Pollution, 2016, 208: 256-260. https://doi.org/10.1016/j.envpol.2015.07.006.
11. TONG Z, CHEN Y, MALKAWI A, et al.. Energy saving potential of natural ventilation in China: The impact of ambient air pollution[J/OL]. Applied Energy, 2016, 179: 660-668. https://doi.org/10.1016/j.apenergy.2016.07.019.
12. Experimental Study on Indoor Air Temperature Distribution of Gravity Air-Conditioning for Cooling[J/OL]. Energy Procedia, 2012, 17: 961-967. https://doi.org/10.1016/j.egypro.2012.02.194.
13. YANG Z, LIU B, ZHAO H. Energy Saving in Building Construction in China: A Review[J/OL]. International Journal of Green Energy, 2004, 1(2): 209-225. https://doi.org/10.1081/GE-120038753.

14. MAILE T, FISCHER M, BAZJANAC V. Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective[J]. Facil. Eng. (CIFE) Working Pap., 2007, 107.
15. A New Pattern Recognition Adaptive Controller with Application to HVAC Systems – ScienceDirect [EB/OL]. [2023-05-13].
https://www.sciencedirect.com/science/article/pii/S0005109898000338.
16. PÉREZ-LOMBARD L, ORTIZ J, POUT C. A review on buildings energy consumption information[J/OL]. Energy and Buildings, 2008, 40(3): 394-398. https://doi.org/10.1016/j.enbuild.2007.03.007.
17. CHEUNG C K, FULLER R J, LUTHER M B. Energy-efficient envelope design for high-rise apartments[J/OL]. Energy and Buildings, 2005, 37(1): 37-48. https://doi.org/10.1016/j.enbuild.2004.05.002.
18. BARRIO E P D. Analysis of the green roofs cooling potential in buildings[J/OL]. Energy and Buildings, 1998, 27(2): 179-193. https://doi.org/10.1016/S0378-7788(97)00029-7.
19. KUMAR R, KAUSHIK S C. Performance evaluation of green roof and shading for thermal protection of buildings[J/OL]. Building and Environment, 2005, 40(11): 1505-1511. https://doi.org/10.1016/j.buildenv.2004.11.015.
20. JAFFAL I, OULDBOUKHITINE S E, BELARBI R. A comprehensive study of the impact of green roofs on building energy performance[J/OL]. Renewable Energy, 2012, 43: 157-164. https://doi.org/10.1016/j.renene.2011.12.004.
21. WONG N H, TAY S F, WONG R, et al.. Life cycle cost analysis of rooftop gardens in Singapore[J/OL]. Building and Environment, 2003, 38(3): 499-509. https://doi.org/10.1016/S0360-1323(02)00131-2.
22. KOSAREO L, RIES R. Comparative environmental life cycle assessment of green roofs[J/OL]. Building and Environment, 2007, 42(7): 2606-2613. https://doi.org/10.1016/j.buildenv.2006.06.019.
23. CHANDEL S S, AGGARWAL R K. Performance evaluation of a passive solar building in Western Himalayas[J/OL]. Renewable Energy, 2008, 33(10): 2166-2173.
https://doi.org/10.1016/j.renene.2008.01.008.
24. CHAN H Y, RIFFAT S B, ZHU J. Review of passive solar heating and cooling technologies[J/OL]. Renewable and Sustainable Energy Reviews, 2010, 14(2): 781-789.
https://doi.org/10.1016/j.rser.2009.10.030.
25. LIANG C hua, ZHANG X song, LI X wei, et al.. Study on the performance of a solar assisted air source heat pump system for building heating[J/OL]. Energy and Buildings, 2011, 43(9): 2188-2196. https://doi.org/10.1016/j.enbuild.2011.04.028.
26. AGRAWAL P C. A review of passive systems for natural heating and cooling of buildings[J/OL]. Solar & Wind Technology, 1989, 6(5): 557-567. https://doi.org/10.1016/0741-983X(89)90091-X.
27. CHI F, XU L, PENG C. Integration of completely passive cooling and heating systems with daylighting function into courtyard building towards energy saving[J/OL]. Applied Energy, 2020, 266: 114865. https://doi.org/10.1016/j.apenergy.2020.114865.
28. Application of an energy management and control system to assess the potential of different control strategies in HVAC systems[J/OL]. Energy and Buildings, 2010, 42(11): 2258-2267. https://doi.org/10.1016/j.enbuild.2010.07.023.
29. THE FLUID MECHANICS OF NATURAL VENTILATION | Annual Review of Fluid Mechanics [EB/OL]. [2023-05-07]. https://www.annualreviews.org/doi/10.1146/annurev.fluid.31.1.201.
30. TONG Z, CHEN Y, MALKAWI A, et al.. Quantifying the impact of traffic-related air pollution on the indoor air quality of a naturally ventilated building[J/OL]. Environment International, 2016, 89-90: 138-146. https://doi.org/10.1016/j.envint.2016.01.016.
31. VAN HOOFF T, BLOCKEN B, TOMINAGA Y. On the accuracy of CFD simulations of cross-ventilation flows for a generic isolated building: Comparison of RANS, LES and experiments[J/OL]. Building and Environment, 2017, 114: 148-165. https://doi.org/10.1016/j.buildenv.2016.12.019.
32. BRAGER G, DE DEAR R. A Standard for Natural Ventilation[J/OL]. 2000[2023-05-09].
https://escholarship.org/uc/item/3f73w323.
33. CHEN Y, TONG Z, MALKAWI A. Investigating natural ventilation potentials across the globe: Regional and climatic variations[J/OL]. Building and Environment, 2017, 122: 386-396. https://doi.org/10.1016/j.buildenv.2017.06.026.
34. OROPEZA-PEREZ I, ØSTERGAARD P A. Energy saving potential of utilizing natural ventilation under warm conditions – A case study of Mexico[J/OL]. Applied Energy, 2014, 130: 20-32. https://doi.org/10.1016/j.apenergy.2014.05.035.
35. JIANG Y, ALEXANDER D, JENKINS H, et al.. Natural ventilation in buildings: measurement in a wind tunnel and numerical simulation with large-eddy simulation[J]. J. Wind Eng. Ind. Aerodyn., 2003.
36. CHAICHANA C, CHARTERS W W S, AYE L. An ice thermal storage computer model[J/OL]. Applied Thermal Engineering, 2001, 21(17): 1769-1778. https://doi.org/10.1016/S1359-4311(01)00046-1.
37. MARDIANA-IDAYU A, RIFFAT S B. Review on heat recovery technologies for building applications[J/OL]. Renewable and Sustainable Energy Reviews, 2012, 16(2): 1241-1255. https://doi.org/10.1016/j.rser.2011.09.026.
38. CRAWLEY D B, HAND J W, KUMMERT M, et al.. Contrasting the capabilities of building energy performance simulation programs[J/OL]. Building and Environment, 2008, 43(4): 661-673. https://doi.org/10.1016/j.buildenv.2006.10.027.

39. SHIN M, HABERL J S. Thermal zoning for building HVAC design and energy simulation: A literature review[J/OL]. Energy and Buildings, 2019, 203: 109429. https://doi.org/10.1016/j.enbuild.2019.109429.
40. FONG K F, HANBY V I, CHOW T T. HVAC system optimization for energy management by evolutionary programming[J/OL]. Energy and Buildings, 2006, 38(3): 220-231.
https://doi.org/10.1016/j.enbuild.2005.05.008.