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Influence of outdoor air on energy consumption of residential buildings in northern China with passivhaus technology

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ABSTRACT

The high demand of passivhaus technology for building envelop improves the insulation property and air tightness, which effectively decreases the cold or heat loss caused by thermal conductivity and air infiltration. However, in order to meet the requirement of indoor sanitation and thermal comfort, ventilation and air conditioning are necessary, thus the energy consumption of air handling and distribution is more prominent. Based on the differences between passivhaus standard and domestic relevant design standard for energy efficiency of residential buildings, builds the different models for comparison. Performs simulation and contrastive analysis about cooling and heating load, as well as energy consumption of ventilation and air conditioning systems under different levels of outdoor air in residential buildings in Beijing. The results show that when the minimum outdoor air volume is 30 m³/(person·h), the maximum heat load of passivhaus standard model is 22W/m^2, and the maximum cooling load is about 55W/m^2, where the outdoor air load can occupy 63.8% and 34.2% in winter and summer, respectively. A certain degree of energy utilization efficiency can be obtained by using mechanical ventilation and energy recovery devices. Then the heating and cooling energy consumption of passivhaus standard model can be 22.66 kW·h/(m^2·a), which saves energy by about 7% than the model with *Design standard for energy efficiency of residential buildings.*

Keywords: passivhaus, residential building, outdoor air load, energy recovery, simulation

NONMENCLATURE

Abbreviations	
HAVC	Heating, ventilating and air conditioning
Symbols	
a	Year

1. INTRODUCTION

In order to cope with climate change and realize sustainable development strategy, all countries are actively formulating medium and long-term development goals and policies for buildings to move towards lower energy consumption. The ultra-low energy consumption building technology system represented by passivhaus is rapidly promoted in China, especially in the north. According to the consensus among European scholars engaged in architectural research and design, the buildings whose annual heating consumption does not exceed 15kW·h/(m^2·a) and the annual total energy consumption (the sum of energy consumption of heating, air conditioning, domestic hot water, lighting and household appliances) does not exceed 120kW·h/(m^2·a) is called "passivhaus"[1] or “passive house”[2]. In order to meet the annual heating consumption and annual total energy consumption index, the envelope structure of passivhaus is required to have excellent thermal insulation and air tightness [3]. The former can well reduce the cold and heat load

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caused by indoor and outdoor temperature difference, while the latter can effectively reduce the cold and heat loss caused by indoor and outdoor air infiltration [4]. However, the indoor air and outdoor exchange need to be achieved through controllable mechanical system [5]. At the same time, there must be certain amount of outdoor air to meet the needs of indoor occupants. The handling, transmission and distribution of outdoor air need to consume a certain amount of energy. Due to the excellent thermal insulation performance of the passive building envelope, the energy consumption of the outdoor air system accounts for a large proportion of the energy consumption of the overall heating and air conditioning system [6].

In this paper, according to the relevant technical parameters requirements of international passive housing and DB11 / 891-2012 "Beijing residential building energy efficiency design standard"[7], a comparative model is established to calculate the indoor load of a residential building in winter and summer as well as the proportion of outdoor air load, to simulate the annual energy consumption situation, to compare and analyze building energy saving capability between the residential building adopting passivhaus technology and domestic design standards in northern China.

2. IMPACT OF TECHNICAL PARAMETERS ON ENERGY CONSUMPTION OF HVAC SYSTEM

2.1 Thermal insulation of building envelope

As shown in Table 1, the limit values of heat transfer coefficient of building envelope such as roof, exterior wall, outer door and window are shown in Table 1.

Table1 Thermal Performance Limits of Building Envelope about Passivhaus Standard and Domestic Energy Efficiency Design Standards for Residential Buildings(W/m² · K)

Terms	Requirements of Building Envelope of Passivhaus Standard [7]	Design Standard for Energy Efficiency of Residential Buildings [7,9]
Heat transfer coefficient of the roof	0.15	0.20~0.45
Heat transfer coefficient of the exterior wall	0.15	0.25~0.60
Heat transfer coefficient of the basement ceiling without heating	0.15	0.35~0.60
Heat transfer coefficient of the exterior door	0.80	1.50~2.0
Heat transfer coefficient of the outside window	0.80	1.50~2.8

At the same time, the passivhaus also requires good treatment of building cold bridge [2,7].

The higher thermal insulation performance of passive building envelope can significantly reduce the heat load caused by heat conduction of envelope structure in winter. But for summer night and transition season, the influence of good thermal insulation performance on building energy consumption needs to be analyzed according to different regional climate conditions.

2.2 Indoor air tightness

According to the German passivhaus standard, the air tightness of the house is $N_{50} \leqslant 0.6/h^{-1}$ [8], that is, when the indoor and external pressure difference is 50pA, the air change frequency per hour is less than 0.6. Domestic residential building standard requires that: external windows and doors (and open balcony doors) should have good air tightness performance. In different climatic zones, the air tightness level should not be lower than the corresponding level in the GB / T7106-2008 *Classification and test methods for air tightness, water tightness and wind pressure resistance performance of building external doors and windows*. The classification index in the standard is based on the corresponding permeability under 10 Pa pressure difference, but there is no requirement for the overall indoor air tightness. In the control of the cooling and heating load caused by infiltration, the passive room has obvious advantages.

2.3 *Indoor outdoor air volume*

To maintain indoor health and comfort, it is necessary to intake a certain amount of outdoor air. In European countries, the design index of outdoor air volume is about 0.4-0.9h^{-1}. Refer to *ASHRAE standard 62.1*, the requirements of GB 50736-2012*Code for design of heating, ventilation and air conditioning of civil buildings* for residential buildings equipped with outdoor air system are shown in the first two columns of Table 2. The data in the third column is the expressions converted into per capita hourly outdoor air volume. At present, the living area per capita is about 30m^2 in China, the minimum designed indoor-outdoor air volume per capita is generally 30m^3 / (person·h). In some countries, it can reach 90m^3/ (person·h) in certain room area according to different requirements of indoor environment [10].

Table2 Minimum Air Changes and outdoor Air Volume in Residential Building Design

Living Area per Capita(Fp)	Air Changes per Hour	outdoor Air Volume per Capita According to the Net Floor Height of 2.8m （m^3/(h·person)
Fp≤10m^2	0.70	19.6
10m^2＜Fp≤20m^2	0.60	16.8~33.6
20m^2＜Fp≤50m^2	0.50	28~70
Fp＞50m^2	0.45	＞63

In China's residential buildings, opened windows and the penetration of the gap between the doors and windows are common ways to achieve building outdoor air ventilation. However, the passivhaus needs mechanical methods to complete the ventilation. The indoor dirty air is discharged into the air duct from the kitchen and toilet exhaust outlet, and the outdoor air enters the room from the air supply intake of the living room and bedroom. In the actual operation process, the indoor CO_2 concentration is monitored to control the outdoor air supply amount, and the indoor CO_2 volume fraction is required to be less than 1000×10^{-6}, which reduces the operation time and energy consumption of outdoor air supply equipment to a certain extent.

At the same time, because the passivhaus has relatively strict requirements on the annual energy consumption per unit area of the building, it is necessary to use devices that are convenient for energy recovery to preheat or precool the outdoor air, so as to achieve lower heating and air conditioning energy consumption [8]. At present, the efficiency of heat recovery device based on sensible heat recovery (HRV) has reached 99%, while that of energy recovery device with total heat recovery (ERV) can reach 60% ~ 90% [11]. The heat recovery device can save part of the energy consumption of outdoor air treatment, yet increase the corresponding equipment operation and maintenance consumption. There are no relevant requirements in current domestic standards for residential buildings [12].

3. COMPUTATIONAL SIMULATION

In view of the above factors, in order to clearly compare the proportion of various loads in the heating and air conditioning of passivhaus to those of ordinary residential buildings, referring to the corresponding technical indicators of passivhaus, the EnergyPlus software is used for computational simulation. The software has feedback of building load, system and equipment during the calculation process, which has good accuracy.[13]

3.1 *Basic parameters of building model*

This paper takes Beijing as the building location. The relevant parameters and spatial dimensions of the model are shown in Table 3 and figures 1 and 2.

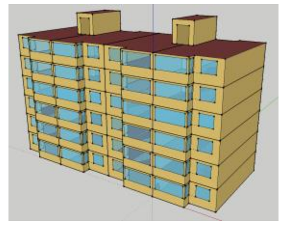

Fig 1 Small diagram

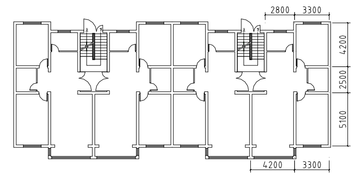

Figure2 Floor Plan of Building

Table3 Basic Parameters of Building Model

Parameters		Value
Location		Beijing
Households		24
Area of Building		1956m2
Layers		6
Floor Height		2.8m
Body Shape Factor（A/V）		0.194
Glazing	South	0.38
Ratio	North	0.21
Staircase		Area without heating and air-conditioning
Balcony		Closed, connected to heating and air conditioning area

3.2 *Parameter condition setting*

The software EnergyPlus V8-1 is used for calculation and simulation. According to the corresponding standards, the main parameter settings of envelope structure, air conditioning system and heat recovery device are shown in the table 4

The process of air in heat recovery device and the HVAC system is shown in Fig. 3.

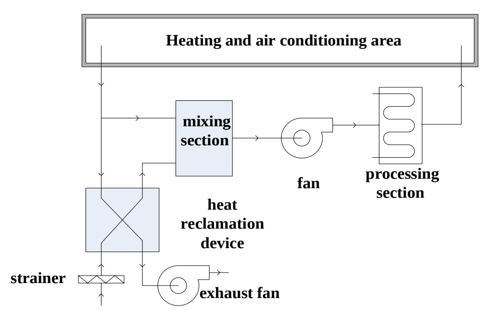

Figure 3. Heating and air conditioning system using heat recovery diagramSmall diagram.

Table 4 Main parameter settings of simulation software [14-17]

Parameter		Corresponding settings in software	Setting value or description
Meteorological parameters		CHN_Beijing.Beijing.545110_ CSWD	Typical meteorological year data of Beijing
Time step		15min	
Calculation duration		1 a	
Envelop	roof and exterior wall	Heat transfer coefficient: Passivhaus is 0.15W/(㎡·K), external wall of common residential buildings is 0.4 W/(㎡·K), roof common residential buildings is 0.35 W/(㎡·K), exposure to sunlight and wind	The model of common residential buildings' value is taken from DB 11/891-2012 *Beijing design standard for energy efficiency of residential buildings*
	out door and window	Heat transfer coefficient: Passivhaus is 0.8W/(㎡·K), common residential buildings is 1.8 W/(㎡·K), exposure to sunlight and wind	The model of common residential buildings' value is taken from DB 11/891-2012 *Beijing design standard for energy efficiency of residential buildings*
	partition wall separating heated and unheated spaces, in a stairwell	Heat transfer coefficient: 0.15W/(㎡·K)	The boundary conditions are calculated according to the temperature difference between the two sides
	indoor wall, inter house wall and ceiling		Heat transfer between rooms is not considered
	Entrance doors	Heat transfer coefficient: 0.8W/(㎡·K)	The boundary conditions are calculated according to the temperature difference between the two sides
inner heat gain	Personnel	0.03 person/㎡	
	lighting	11W/㎡	
	equipment	11 W/㎡	
Outdoor air volume		30-90 m³/(person·h)	Several calculations were carried out in the step of 15 m³/(person·h).
HAVC	indoor design parameter	Cooling design supply air temperature is 18℃. Heating design supply air temperature is 26℃. Heat/ cooling design supply air humidity radio is 12g/kg.	
	System control and mode	Constant heating setpoint is 18℃. Constant cooling setpoint is 26℃. System type is heat pump system and variable refrigerant flow system. Gross rated heating COP is 2.8. Gross rated cooling COP is 3.0.	The problems that may occur in actual operation, such as frosting on outdoor coil of air source heat pump in winter, are not considered
Heat recovery unit	Selection of heat exchanger	Air to air; sensible and latent	Total heat recovery
	Heat recovery efficiency at rated air volume	Sensible effectiveness at 100% airflow heating condition is 0.806. Latent effectiveness at 100% airflow heating condition is 0.678. Sensible effectiveness at 75% airflow heating condition is 0.843. Latent wffectiveness at 75% airflow heating condition is 0.717. Sensible Effectiveness at 100% Airflow Cooling Condition: 0.806. Latent Effectiveness at 100% Airflow cooling Condition: 0.678. Sensible Effectiveness at 75% Airflow Cooling Condition: 0.843. Latent Effectiveness at 75% Airflow Cooling Condition: 0.717.	Select a heat recovery device with total heat recovery efficiency higher than 75%

4. RESULT ANALYSIS

4.1 *General situation of load*

The maximum load and outdoor air load of the whole building calculated according to the international passivhaus technical standard and the energy saving standard of Beijing residential building are shown in Table 5.

Table 5. Building load maximum point and other indicators simulated calculation (calculation of outdoor air volume 30 $m^3/(h \cdot person)$)

Building model	Germany's passive house requirements		Beijing residential building energy saving design standard	
	Summer cooling	Winter heating	Summer cooling	Winter heating
Peak load [W]	108248（100395）	42061（24184）	98980	61335
Peak load per unit area [W/m^2]	55.3（51.3）	22（12.4）	50.6	31.4
Average load per unit area [W/m^2]	13.3（10.8）	12.9（7.3）	11.8	14.5
Peak load time	2014/7/21 14:15	1/21 24:00:00	2014/7/21 13:00	1/21 24:00:00
Outdoor temperature at peak load [℃]	34.9	-10.8	37.7	-10.8
Outdoor air conditioning humidity at peak load [kgWater/kgAir]	0.01165	0.00149	0.01161	0.00149
outdoor air volume [m^3/h]	1755.84	1728	1755.84	1728
Peak outdoor air load [W]	15145（5741）	26866（8989）	15145	26866
Peak outdoor air load per unit area [W/m^2]	7.8（3.0）	13.7（4.6）	7.8	13.7
Peak outdoor air load time	2014/7/21 8:00	1/21 24:00:00	2014/7/21 8:00	1/21 24:00:00

Note 1. The heat load calculation method of air conditioning is adopted for heating in winter.

Due to the good thermal insulation performance of passivhaus building envelope, the corresponding model heat load is 22 w/m^2 without heat recovery device in winter, which is about 67% of the model heat load (31.4 w/m^2) in *Beijing residential building energy efficiency design standard model* (DB11 / 891-2012). In summer, the maximum load point of passivhaus appears at 14:15. As shown in Figure 4, the cooling load is 55.3w/m^2, which is higher than 50.6w/m^2 of the model in *Beijing residential building energy efficiency design standard model* (DB11 / 891-2012). If the passivhaus model adopts exhaust heat recovery, the two are roughly the same.

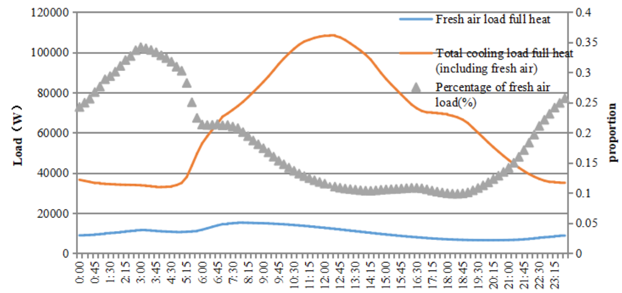

Figure 4 Changes of indoor outdoor air load and total cooling load in summer

Analysis of the possible reasons: there are obvious differences in the geographical latitude between China and Germany. The latitude of Germany ranges from N48° to N54° and that of Berlin is about N52°, while the latitude of several major cities in northern China, such as Urumqi and Harbin, is about N45°. The difference of latitude directly leads to the difference of indoor solar heat gain in different seasons, which leads to the difference of indoor cooling and heating load in winter and summer. In summer, the good thermal insulation performance and high air tightness of passivhaus can effectively reduce the indoor heat gain, but it is also inconvenient for heat dissipation of the room. Therefore, there is no obvious differences between passivhaus and those designed according to residential building energy efficiency standards.

4.2 *Proportion of outdoor air load*

In summer, the maximum outdoor air load is not appeared at the same time with the total load. As shown in Figure 4, when the outdoor air volume is 30m^3 /(person • h), the ratio of outdoor air load to total load on a certain day in summer changes with time. The highest value appears at 03:00, which is 34.2%, and the average value in summer is 18.4% (time average). With the different outdoor air volume, the corresponding proportion varies from 14% to 34%, as shown in Figure 5.

In winter, due to the good thermal insulation performance of passivhaus, the cooling and heating load generated by the envelope structure is effectively reduced, and the heat dissipation of indoor human body, lamps and equipment are well utilized, so the outdoor air load is bigger. According to the different outdoor air volume, the outdoor air load accounts for about 63.8% ~ 84.1% of the total heat load without heat recovery, as shown in Figure 6.

When the total heat recovery (ERV) device is used and the outdoor air volume is 30m^3 / (person·h), the outdoor air load in summer is reduced by 63% and that in winter is reduced by 67%. The outdoor air load in summer is reduced to 7.4% of the total cooling load, and the maximum outdoor air load in winter is reduced to 37.16% of the total heat load, and other outdoor air flow levels decrease more obviously, as shown in figures 5 and 6.

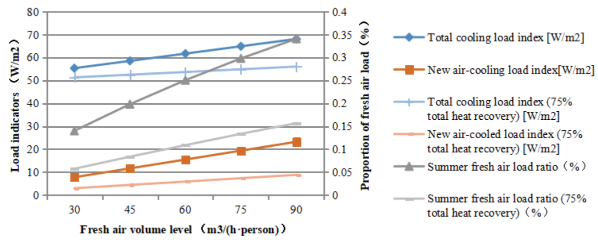

Figure 5. Proportion of summer outdoor air load at different outdoor air volume levels and total heat recovery

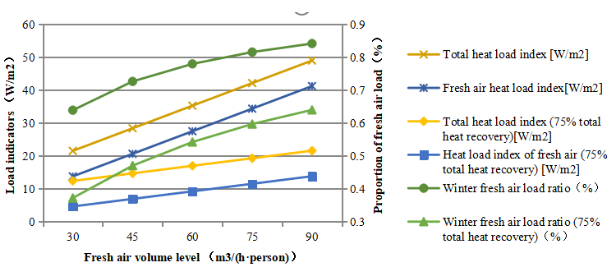

Figure 6. Proportion of winter outdoor air load at different outdoor air volume levels and total heat recovery

4.3 *Energy consumption of heating and air conditioning system*

Figure 7 shows the heating and air conditioning energy consumption of passivhaus and general energy-saving buildings in winter and summer under the conditions of different outdoor air volume and whether heat recovery devices are used.

Using energy recovery device can save energy by 5.47% ~ 11.2% in the whole year. When the outdoor air volume is 30m^3 / (person·h), the energy consumption of the energy recovery device is 3.1 kW·h/(m^2·a), accounting for 10.96% of the annual energy consumption of the system, while the cooling energy consumption in summer is 16.04 kW·h/(m^2·a), accounting for about 75% of the annual energy consumption of the system.

The outdoor air volume affects a lot on annual energy consumption of passivhaus heating and air conditioning system. When the outdoor air volume is set at 90m^3 / (person·h), the annual system energy consumption will reach 33.35 kW·h/(m^2·a), 47% higher than that of 30m^3 / (person·h).

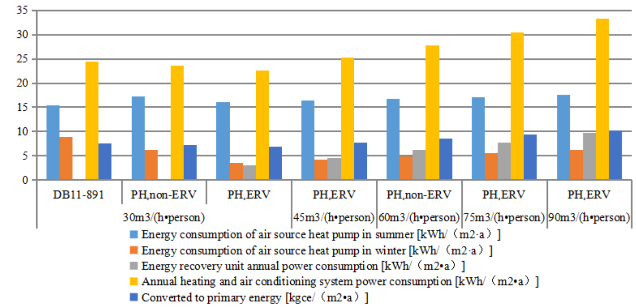

Figure 7. Comparison of annual energy consumption in various situations

(Note: DB11-891, According to Beijing residential building energy-saving design standards (DB11-891-2012) calculation; PH: "passivhaus "; non-ERV: no energy recovery device; EVR: the use of energy recovery devices. The electric power is converted into standard coal 1 kwh=0.308 kgce.)

The annual energy consumption of the heating and air conditioning system of the passivhaus is 22.66 kW·h/(m^2·a) with outdoor air volume of 30m^3 / (person·h), which can save energy by 7% compared with the building built according to the Beijing energy saving standard of 24.38 kW·h/(m^2·a) under the same indoor hygiene and thermal comfort conditions.

It should be noted that most domestic residential buildings do not have an independent outdoor air system, whose ventilation mainly relies on natural ventilation and cold air infiltration. In this paper, in order to compare the load and energy consumption level of passivhaus and general energy-saving residential building, the indoor and outdoor air volume and temperature and humidity are set in the same way, so the results may be different from the actual situation.

5. CONCLUSION

1) The outdoor air load of passivhaus is bigger. The use of high efficiency total heat recovery device for outdoor air pretreatment can significantly reduce the outdoor air load, and has certain energy-saving benefits, which is very important for the passivhaus to meet the corresponding energy consumption index requirements.

2) The cooling air conditioning energy consumption of passivhaus in summer is the main energy consumption of the system in the whole year. When promoting high performance buildings such as passivhaus in China, the energy saving demand should be considered comprehensively.

3) The good thermal insulation performance and air tightness of passivhaus have obvious effect on reducing the indoor heating and air conditioning load in winter. But in summer, compared with the residential buildings

built according to the existing energy-saving standards in China, the simulation results show that the cooling load of air-conditioning is not effectively reduced. Under a certain amount of outdoor air, the annual energy saving rate of passivhaus heating and air conditioning is about 7%. Therefore, the applicability of passivhaus technology in China's residential buildings should be further analyzed and judged in combination with other factors such as incremental cost.

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