Influence of Building Air Tightness on Energy Consumption of Ventilation System in Nearly Zero Energy Residential Buildings

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Abstract. Building air tightness increased quickly in recent years as nearly zero energy buildings concept gradually drawn more attentions from the industry. Ventilation system plays an important role for the indoor air quality control in residential buildings with good air tightness. The energy consumption of the ventilation system is a significant part of the overall energy consumption of low energy residential building. The influence of the building air tightness on the energy consumption of ventilation system was not addressed sufficiently in previous studies. This paper analyses the quantitative relations between building air tightness, energy recovery efficiency and ventilation system control strategy. A mathematical model of the heating and cooling energy consumption in residential buildings is proposed, which takes building air tightness, energy recovery efficiency and control strategy of ventilation system as major input parameters. Equivalent COP of ventilation energy recovery system is proposed as an energy efficiency index of the ventilation system. It can be used as a criterion to decide the optimal design parameters of nearly zero residential buildings in different climate conditions.

1 Introduction

Building air tightness is an important performance indicator of the nearly zero energy buildings. Different climate zones should have different building airtightness requirements. This is especially true for the countries like China who has a vast territory and complex climate conditions. In the "Technical Guidelines for Passive Low Energy Residential Buildings" published by Chinese government in 2015 [1], a reference value from the European standard was adopted. It was required that the low energy residential buildings should has airtightness of 0.6 air changes per hour at 50 Pascals pressure (hereinafter referred to as N_{50}). With good building air tightness, the energy loss caused by the air infiltration can be greatly reduced. On the other hand, the mechanical ventilating system becomes necessary in such buildings of good airtightness, which consumes additional energy. An optimal trade-off exists between the energy saving from the heat recovery of exhausted air and the additional energy consumption of the mechanical ventilation system. In different climatic conditions, the quantitative relationships between the energy consumption of ventilation, building air tightness, and heat recovery efficiency are different.

Many studies addressed the of the impact of building air tightness on building energy consumptions. The ISO 13790-2008 standard [2] gives the effect of air infiltration on the energy consumption of building ventilation systems. Jokisalo [3] studies that the relationship between airtightness value under test condition and normal

operational condition. Persil [4] conducted long-term test which shows that 33% of the cooling and heating load is caused by the air infiltration. The experiment results indicates that the volum of building infiltration under 50 Pa is about 20 times of that under normal pressure. In China's "Standard for on-site testing of energy efficient civil buildings engineering" DB11/T555, the relational value is 17 times.

Simonson [5] studied Finnish residential buildings and found that for heat recovery efficiency of 70%, 50%, and 0%, the energy consumption would increase by 2.7 kWh/(m²/a), 4.5 kWh/(m²/a) and 9.2kWh/(m²/a) for each 0.1h⁻¹ increase of air exchange rate. At an air exchange rate of 0.5h⁻¹, for every 10% increase in energy recovery efficiency, energy consumption of 3.3kWh/(m²/a) can be reduced. Zhang X.D [6] used building energy simulation tool to calculate the annual load of buildings under different airtightness levels of doors and windows in Nanjing City. When the airtightness is increased from level 1 to level 8, the cumulative load in the heating season is reduced by 51.5%, while the cumulative load in the air conditioning season was reduced by 32.6%, and the cumulative load reduction for the whole year reached 46.7%. Peng C. [7] studied the impact of air tightness on heating energy consumption and found that as the air tightness increased in the hot summer and cold winter climate zone of China, the energy consumption of the fans increased significantly, which causes the total energy consumption of heating increased despite the heat recovery efficiency increase. Most relevant researches use simulation tools to study typical buildings to evaluate the

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importance of air tightness. Detailed analysis of the influence mechanism between the air tightness and building energy consumption, especially the energy consumption of fresh air, is insufficient. The applicability of the research results is constrained by the selection of typical buildings.

Lv Y.J. [9] studied the influence of frost protection and preheating in winter energy recovery devices on energy consumption of nearly zero energy buildings in cold climate zones. A calculation method was proposed to calculate the thermal load and annual cumulative ventilation heating load. Adopting Lv's calculation method, Xu W. [10] proposed a correction method to estimate the deviations of fresh air heating load and energy consumption caused by different operating schedule in office and residential buildings. The energy consumption of fresh air heating in residential buildings can be reduced by 24% to 31% when operational schedule is optimized. For office buildings, the reduction rate can reach 65%. For every 5 °C of increase of preheating set temperature, the recovered heat reduced by 7% to 10%. The above researches only focus on the heating mode of cold climate zones. Further research on other climate zones and cooling mode has not been well addressed.

This paper studies the quantitative relationship between air tightness and energy consumption of ventilation systems in nearly zero energy residential buildings. Considering the usage mode and operating time of ventilation system, the effects of different building air tightness and annual energy consumption of ventilation system in different climate zones, different control strategies and different energy recovery efficiency are analyzed. Equivalent COP of ventilation energy recovery system is proposed as an energy efficiency index of the ventilation system. It can be used as a criterion to decide the optimal design parameters of nearly zero residential buildings in different climate conditions.

2. Ventilation system energy consumption calculation method

2.1 Ventilation volume of buildings

In China, GB 50736-2012 "Design code for heating, ventilation and air conditioning in civil buildings" [11] stipulates that the minimum amount of ventilation required for residential buildings should be determined according to the method of air change rate. The number of air changes in residential buildings should be in accordance with the values given in Table 1.

Table 1. The number of minimum fresh air changes N_s in residential buildings

living area per capita F_p	air changes per hour
$F_p \leq 10\text{m}^2$	0.70
$10\text{m}^2 < F_p \leq 20\text{m}^2$	0.60
$20\text{m}^2 < F_p \leq 50\text{m}^2$	0.50
$F_p > 50\text{m}^2$	0.45

Building design ventilation volume V :

$$V = A \times h \times N_s \quad (1)$$

Where: A is the usable area inside the building, m^2 ; h is the height of the building space used, m ; N_s is the number of air changes, h^{-1} .

The heating and cooling load caused by the air infiltration driven by wind pressure and hot pressure should be taken into the overall building heating and cooling load [12]. According to ISO 13790 [2], the relationship between the air change rate of test condition and normal operation condition is:

$$V_N = 0.3 \times 1.3 \times V_B \quad (2)$$

$$N_{V,Rest} = \frac{V_{N50} \cdot N_{50} \cdot e}{V_N} \quad (3)$$

$$V_{in} = A \times h \times N_{V,Rest} \quad (4)$$

Where: V_N is the ventilation volume under normal operation, m^3/h ; 0.3 is the minimum number of air changes in the building, h^{-1} ; 1.3 is the ventilation correction coefficient; V_B is the usable space volume, m^3 ; $N_{V,Rest}$ is the number of air infiltration changes under normal pressure, h^{-1} ; V_{N50} is the air infiltration under the pressure of 50Pa, m^3/h ; e is the building wind resistance coefficient; V_{in} is the air infiltration under normal pressure, m^3/h .

ISO standard 13790-2008 gives the corresponding wind resistance coefficient e according to the degree of exposure of the building and the degree of occlusion. The value of the wind resistance coefficient is 0.01~0.1.

The ventilation volume of residential building design consists of two parts: air infiltration volume and mechanical ventilation volume. When the fresh air volume requirement is given, if the building has better air tightness, the air infiltration will be smaller, and the corresponding mechanical ventilation volume should be larger to maintain indoor air quality.

$$N_s = N_V + N_{V,Rest} \quad (5)$$

$$V_V = A \times h \times N_V \quad (6)$$

Where: N_s is the number of ventilation takes from table 1; N_V is the number of mechanical ventilating rate, h^{-1} ; V_V is the mechanical ventilation rate, m^3/h .

2.2 The calculation of the ventilation system's cooling and heating load

It is assumed that the ventilation system does not bear the indoor load and only processes to the indoor setting state. The heating load q_1 of the ventilation system consists of the preheating load q_p , the auxiliary heating load q_h (heating load required for mechanical ventilation after energy recovery treatment) and the air infiltration heating load q_{in1} ; cooling season ventilation system load q_2 consists of auxiliary cooling load q_c and air infiltration cooling load q_{in2} .

Heating load:

$$q_1 = q_p + q_h + q_{in1} \quad (7)$$

Cooling load:

$$q_2 = q_c + q_{in2} \quad (8)$$

When the temperature is lower than the minimum operating temperature of the energy recovery device, the frost may grow on the heat recovery unit. The outdoor fresh air needs to be preheated before entering the heat recovery unit, and the preheating set-point temperature is

t_{set} . When the outdoor dry bulb temperature is $t_o < t_{set}$, the preheating load of the ventilation system is:

$$q_p = c_p \rho_{air} V_V (t_{set} - t_o) / 3600 \quad (9)$$

Where: q_p is the preheating load, kW; c_p is the specific heat of air, kJ/(kg·K); ρ_{air} is the air density, kg/m³; t_{set} is the preheating set-point temperature, °C; t_o is outdoor dry bulb temperature, °C.

Calculating the auxiliary heating load of the ventilation system in the heating season should consider two situations: when the outdoor temperature t_o is less than the preheating load set temperature t_{set} , preheating is required, and the auxiliary heating load is calculated using equation (10). If the outdoor temperature t_o is higher than the set temperature t_{set} of the preheating load, the auxiliary heating load is calculated using the equation (11).

$$q_h = c_p \rho_{air} V_V (t_{room} - t_{set}) (1 - \eta_t) / 3600 \quad (10)$$

$$(t_o < t_{set})$$

$$q_h = c_p \rho_{air} V_V (t_{room} - t_o) (1 - \eta_t) / 3600 \quad (11)$$

$$(t_o > t_{set})$$

Where: q_h is the auxiliary heating load of the ventilation system, kW; t_{room} is the indoor design temperature, °C; η_t is the sensible heat exchange efficiency of the total energy recovery unit.

Auxiliary ventilation cooling load in cooling season:

$$q_c = \rho_{air} V_V (h_o - h_{room}) (1 - \eta_h) / 3600 \quad (12)$$

Where: q_c is the auxiliary cooling load of the ventilation system, kW; h_o is the outdoor air enthalpy, kJ/kg; h_{room} is the indoor setting enthalpy, kJ/kg; η_h is enthalpy efficiency of heat recovery unit.

Heating load from infiltration:

$$q_{in1} = c_p \rho_{air} V_{in} (t_{room} - t_o) / 3600 \quad (13)$$

Cooling load from infiltration:

$$q_{in2} = \rho_{air} V_{in} (h_o - h_{room}) / 3600 \quad (14)$$

2.3 Calculation of annual cumulative heating and cooling load caused by ventilation and infiltration

The calculation of the heating load and cooling load caused by ventilation and infiltration is critical for the analysis of energy consumption in nearly zero energy buildings. This paper uses the temperature hours and enthalpy hours method. Given the meteorological data and indoor set values, the heating and cooling loads in equations (7)-(14) are accumulated for 8760 hours. In the equations, Q_{S1} is the accumulated ventilation heat consumption; Q_{S2} is the accumulated cooling capacity; Q_p is the accumulated preheating load; Q_h is the accumulated auxiliary heating quantity, Q_c is the accumulated auxiliary cooling consumption; Q_{in1} is the cumulative heating load caused by infiltration; and Q_{in2} is the cumulative cooling load caused by infiltration, kWh/a.

2.4 Control mode of the ventilation system

In order to obtain the rational relationship between the air tightness of the building and the energy consumption of the ventilation system, the control strategy of the ventilation system should be considered properly. This

paper calculates the quantitative relationship under the following three control modes.

2.4.1 Set schedule mode (Mode 1)

Time schedule can make big difference to the energy consumption of ventilation system. Taking the example of a typical working household, Table 2 gives the operating time table. The following simulation assumes that the ventilation system only runs within the set time.

Table 2 Operating of energy calculation for ventilation system in residential buildings

Status of ventilation system	Work day (Monday to Friday)	Weekend (Saturday and Sunday)
on	19:00 ~ 8:00	00:00 ~ 24:00
off	08:00 ~ 19:00	

2.4.2 Manual control mode (Mode 2)

In the cooling season, when the outdoor temperature is lower than a given value, occupants may tend to improve the indoor environment by opening the window using natural ventilation. Assume 22:00 as the time of occupants to go to sleep, the manual control mode assumes that before 22:00 the occupants will choose to use natural ventilation or mechanical ventilation according to the outdoor environment. In the winter, window opening cannot be used to increase the room temperature. The manual control strategy assumes that mechanical ventilation is the only ventilation mode in winter.

2.4.3 Optimal automatic control mode (Mode 3)

In the cooling season, a thermostat is used to choose between the natural ventilation mode or mechanical ventilation mode according to the outdoor environment. If the outdoor enthalpy is lower than the set value, natural ventilation will be chosen. If the outdoor enthalpy is higher than the set value, mechanical ventilation will be chosen. The decision change can be done at any time of the day without the limitation of sleeping time of occupants.

1.5 Annual heating and cooling energy consumption caused by ventilation and infiltration

Assume electric heating is used for the preheating in the winter to protect the heat recovery unit, and the heating efficiency is taken as 100%:

$$E_p = Q_p \times 100\% \quad (15)$$

Where: E_p is the preheating energy consumption, kWh/a. Assume the auxiliary cooling and heating energy consumption caused by ventilation and infiltration is done by heat pump:

$$E_H = \frac{Q_h + Q_{in1}}{\varepsilon_1} \quad (16)$$

$$E_C = \frac{Q_c + Q_{in2}}{\varepsilon_2} \quad (17)$$

Where: E_H is the heat pump energy consumption for the auxiliary heating, kWh/a, ε_1 is the heating COP of heat pump; E_C is the heat pump energy consumption for the auxiliary cooling, kWh/a, ε_2 is the cooling COP of the heat pump.

Energy consumption of the fan is:

$$E_F = V_V \times P \times T \quad (18)$$

Where: E_F is the energy consumption of the ventilation fan, kWh/a; P is the power consumption of fan per unit air volume, $0.45\text{W}/(\text{m}^3/\text{h})$ [1]; T is the operating time of the fan, h

Equivalent COP of ventilation heat recovery system is proposed as an energy efficiency index, defined as follows:

$$\text{COP}_1 = \frac{Q_1}{E_1} \quad (19)$$

$$E_1 = E_P + E_H + E_F \quad (20)$$

Where: COP_1 is the equivalent COP of ventilation heat recovery system in the heating season; E_1 is the total energy consumption of the ventilation system in the heating season, kWh/a; Q_1 is the total heating load of the fresh air, and the energy required to process the outdoor air to the indoor set parameters, kWh/a.

$$\text{COP}_2 = \frac{Q_2}{E_2} \quad (21)$$

$$E_2 = E_C + E_F \quad (22)$$

Where: COP_2 is the equivalent COP of ventilation heat recovery system in the cooling season; E_2 is the total energy consumption of the ventilation system in the cooling season, kWh/a; Q_2 is the total cooling load of the fresh air, and the energy required to process the outdoor air to the indoor design parameters, kWh/a.

Equivalent COP of ventilation heat recovery system is proposed as an energy efficiency index. Without heat recovery system, all the heating and cooling load for fresh air supply will be taken by the heat pump. Therefore, if the equivalent COP is higher than the heat pump COP, the ventilation heat recovery system is more efficient than the traditional ventilation system without heat recovery, and vice versa.

3 Calculation results and analysis

This paper selects four typical cities in different climate zones of China (Harbin, Beijing, Nanjing, Guangzhou), and studies the effects of building air tightness on annual energy consumption of ventilation system using different different control strategies with different energy recovery efficiency.

From the equations (7) and (8), it can be seen that the energy consumption of ventilation system has nothing to do with the thermal parameters of building envelope, household type, window-wall ratio and other factors, and is directly proportional to the area of the building envelope. Therefore, this paper discusses the energy consumption of fresh air per unit area of the building envelope. Following values are chosen in the simulation: the indoor temperature is 20°C ; the summer indoor temperature setpoint is 26°C ; the relative humidity setpoint is 50%; the enthalpy setpoint is 53kJ/kg . The preheating start when the outdoor temperature is below -10°C . The air source heat pump is used for both winter heating and summer cooling. In winter, the heat pump COP of Harbin is taken as 1.5, the heat pump COP of

Beijing in winter is taken as 2.5, and for the rest is taken as 3.5. The meteorological parameters are calculated as 8760 hours of meteorological parameters for different city built by the energy simulation software DeST. It used the generated meteorological parameters based on the measured data of 194 meteorological points provided by the China National Meteorological Center for 50 years [13].

3.1 Energy consumption of ventilation system without natural ventilation (Mode 1)

The ventilation system is used during the actual operating time in the building, without natural ventilation.

3.1.1 Severe cold climate zone

Figure 1 shows the energy consumption and equivalent COP ventilation system under different air tightness in Harbin (Severe Cold Climate). When the N_{50} is reduced from 1.3 to 0.3, the energy consumption of the ventilation system in the heating season is reduced by $7.51\text{ kWh}/(\text{m}^2 \cdot \text{a})$, accounting for 26%, and the equivalent COP of the ventilation energy recovery system is increased by 0.8. Harbin is located in the severe cold area, where the outdoor minimum temperature can reach -30°C in winter, and the outdoor temperature is lower than -10°C for most of the time in winter. The heat recovery unit use a lot of energy to preheat the outdoor air. When N_{50} decreases from 1.3 to 0.3, the energy consumption of ventilation system increases by $0.13\text{ kWh}/(\text{m}^2 \cdot \text{a})$ in the cooling season, and the equivalent COP is also lower than that of the heat pump. It is mainly because that the temperature difference between indoor and outdoor in Harbin is small in summer. When the mechanical ventilation unit is turned on, the energy consumption of the fan is relatively large, whereas the energy recovery unit has relatively small benefit

Fig.1. Energy consumption and equivalent COP of ventilation system under different air tightness in Harbin

3.1.2 Cold climate zone and hot summer and cold winter climate zone

Figure 2 and Figure 3 show the energy consumption and equivalent COP of the ventilation system in Beijing and Nanjing respectively. When the N_{50} decreased from 1.3 to

0.3, the energy consumption of the ventilation system in the heating season in Beijing and Nanjing is reduced by 32% and 23% respectively and the equivalent COP increased by 1.92 and 1.48. When the N_{50} decreased from 1.3 to 0.3, the energy consumption of the ventilation system in the cooling season in Beijing and Nanjing decreased by 7% and 20% respectively, and the equivalent COP of the ventilation energy recovery system increased by 0.3 and 1.2. Beijing's energy consumption in the cooling season has not decreased significantly with the decrease of N_{50} , which is mainly because Beijing has a large amount of time during the operating hours in summer when the outdoor enthalpy is lower than the indoor set value. The heat recovered by the heat recovery unit is less than that of Nanjing while the fan is in in full-time operation mode and consumes a lot of energy.

Fig.2. Energy consumption and equivalent COP of ventilation system under different air tightness in Beijing

Fig.3. Energy consumption and equivalent COP of ventilation system under different air tightness in Nanjing

3.1.3 Hot Summer and Warm Winter Climate Zone

Fig.4. Energy consumption and equivalent COP of ventilation system under different air tightness in Guangzhou
Guangzhou is in the hot summer and warm climate zone, where the average monthly temperature in winter is higher

than 10 °C and does not require heating in winter. Figure 4 shows the energy consumption and equivalent COP of the ventilation system in the cooling season of Guangzhou. When the N_{50} is reduced from 1.3 to 0.3, the energy consumption of the ventilation system reduced by 22%, and the equivalent COP of the ventilation energy recovery system increased by 1.38.

In all climate zones, when there is no natural ventilation, the improvement of air tightness can reduce the total energy consumption of cooling and heating of ventilation system to different degrees, which improves the equivalent COP of ventilation energy recovery system.

3.2 Summer energy consumption of ventilation system under manual control (Mode 2)

Fig.5. The relationship between energy consumption and air tightness of ventilation system under manual control in different climatic zones during cooling season

In real situation, people tend to open window when the outdoor environment is better than the indoor environment. Figure 5 shows the energy consumption and equivalent COP of the ventilation system in the cooling season of typical cities in different climate zones under the manual controlled mode. Compared with the closed window mode, the energy consumption is lower, and the efficiency is higher. When the N_{50} decreased from 1.3 to 0.3, the energy consumption in Guangzhou and Nanjing decreased more, by 22% and 23% respectively, and the system equivalent COP increased by 1.4 and 1.5. The energy consumption in Beijing and Harbin decreased by 15.4% and 3.2% respectively.

Taking $N_{50}=0.6$ as an example, the energy consumption of Guangzhou, Nanjing, Beijing and Harbin decreased by 1.3%, 2.7%, 18.9% and 31.4% respectively in manual mode (Mode 2), compared to the mechanical ventilation only mode (Mode 1). The energy consumption of Beijing and Harbin decreased by a larger percentage.

3.3 Energy consumption of ventilation with optimal automatic control (Mode 3)

Figure 6 shows the energy consumption and equivalent efficiency of the ventilation system under the optimal automatic control mode (Mode 3) in the cooling season of different climate zones. Compared to the manual control mode, the energy consumption in Harbin can be reduced

by 5% to 10%, and the energy consumption in other zones is basically the same.

Fig.6. The relationship between energy consumption and air tightness of ventilation system under optimal automatic control in different climatic zones during cooling season

A switching enthalpy setpoint is used to switch between the use of natural ventilation and mechanical ventilation. It is discussed whether switching enthalpy setpoint will have an impact on the above result. Because the energy consumption for cooling in Harbin is trivial, the following are only discussed among Beijing, Nanjing and Guangzhou. Figure 7 shows the equivalent COP of energy recovery system in Beijing, Nanjing, and Guangzhou under different opening enthalpy during the cooling season.

Under the same air tightness and the same set opening enthalpy, the equivalent COP of Guangzhou is the highest, while that of Beijing is the lowest. When N_{50} is 0.6 and 1, the energy consumption reaches the lowest value and the equivalent COP reaches the highest value when the opening enthalpy is about 59 kJ/kg. When the number of air changes N_{50} is 0.6 and 1, the equivalent COP of Beijing system is increased by 0.28 and 0.2 respectively. The equivalent COP of Nanjing system is increased by 0.2 and 0.13 respectively, and the equivalent COP of Guangzhou system is increased by 0.08 and 0.06 respectively.

Fig.7. Equivalent COP of ventilation system under different setting enthalpy values in different climate zones

3.4 Energy consumption of ventilation system under different energy recovery efficiency

Sections 2.1-2.3 show the relationship between the air tightness, the energy consumption and the equivalent COP of ventilation system in different climatic zones.

This section further analyses the influence of different energy recovery efficiency on the above relationship.

Figure 8 and Figure 9 show the energy consumption and equivalent COP of the ventilation system in the heating season and cooling season in Beijing under different energy recovery efficiency. As the energy recovery efficiency increases, the energy consumption of the ventilation system in the heating season and the cooling season decreases, and the equivalent efficiency increases as the energy recovery efficiency increases. When the heat recovery efficiency is lower than 60%, the equivalent COP is not sensitive to the airtightness. The equivalent COP increases rapidly as the energy recovery efficiency increases. When the heat recovery efficiency is higher than 60%, and N_{50} is 0.6, the equivalent COP of the system is obviously higher than that of N_{50} is 1, and the difference increases as the energy recovery efficiency increases.

For every 0.1 increase in sensible heat recovery efficiency, the energy consumption of the ventilation system decreased by 8.8% and 7.6%, respectively, when the N_{50} was 0.6 and 1 during the heating season. For every 0.1 increase in enthalpy recovery efficiency, the energy consumption of ventilation system decreased by 7.7% and 6.9%, respectively, when the N_{50} of the cooling season was 0.6 and 1.

Fig.8. Energy consumption of ventilation system under different energy recovery efficiency in Beijing heating season

Fig.9. Energy consumption of ventilation system under different energy recovery efficiency in Beijing cooling season

Figure 8 and Figure 9 show the energy consumption and equivalent COP of the ventilation system in the heating season and cooling season in Beijing under different energy recovery efficiency. As the energy recovery efficiency increases, the energy consumption of the ventilation system in the heating season and the cooling season decreases, and the equivalent efficiency increases as the energy recovery efficiency increases. When the heat recovery efficiency is lower than 60%, the

equivalent COP is not sensitive to the airtightness. The equivalent COP increases rapidly as the energy recovery efficiency increases. When the heat recovery efficiency is higher than 60%, and N_{50} is 0.6, the equivalent COP of the system is obviously higher than that of N_{50} is 1, and the difference increases as the energy recovery efficiency increases.

For every 0.1 increase in sensible heat recovery efficiency, the energy consumption of the ventilation system decreased by 8.8% and 7.6%, respectively, when the N_{50} was 0.6 and 1 during the heating season. For every 0.1 increase in enthalpy recovery efficiency, the energy consumption of ventilation system decreased by 7.7% and 6.9%, respectively, when the N_{50} of the cooling season was 0.6 and 1.

Fig.10. Energy consumption of ventilation system under different energy recovery efficiency in Nanjing heating season

Fig.11. Energy consumption of ventilation system under different energy recovery efficiency in Nanjing cooling season

Figure 10 and Figure 11 show the energy consumption and equivalent COP of the ventilation system in the heating season and cooling season in Nanjing under different energy recovery efficiency. The trend of energy consumption and equivalent COP in Nanjing is consistent with that in Beijing. For every 0.1 increase in sensible heat recovery efficiency, the energy consumption of the ventilation system decreased by 8.0% and 7.0%, respectively, when the N_{50} was 0.6 and 1 during the heating season. For every 0.1 increase in enthalpy recovery efficiency, the energy consumption of ventilation system decreased by 8.2% and 7.2%, respectively, when the N_{50} of the cooling season was 0.6 and 1.

As the energy recovery efficiency increases, the energy consumption of the ventilation system decreases, and the equivalent COP of the ventilation energy recovery system increases. Especially under high energy recovery

efficiency conditions, the improvement of air tightness can effectively improve the system equivalent COP.

4 Conclusion

1) When the only ventilation mode is mechanical ventilation, with the improvement of building air tightness, heating energy consumption in different climate zones decreases, and the equivalent efficiency of ventilation energy recovery system increases. In the cooling season, as the air exchanges rate N_{50} decreased, the energy consumption of the ventilation system in Harbin increased slightly. The cooling energy consumption in the other three typical cities is reduced, and the equivalent COP of the energy recovery system increased.

2) In the cooling season, considering the human behaviour by allowing manual operation of the window, the energy consumption of ventilation system is lower than that without natural ventilation, and the equivalent COP of ventilation energy recovery system is higher. With the improvement of air tightness, the energy consumption of ventilation system in Nanjing and Guangzhou decreases by 23% and 22% respectively.

3) In the cooling season, using optimal automatic control mode, the overall trend of energy consumption and equivalent COP of the ventilation system are similar to that of the manual control mode. An optimum value exists which can minimize the energy consumption and maximize the equivalent COP of ventilation system.

4) Under the same air tightness, the energy consumption of ventilation system decreases with the increase of energy recovery efficiency, and the equivalent COP of ventilation energy recovery system increases as the energy recovery efficiency increases. Under high energy recovery efficiency, the system equivalent COP with good air tightness is higher than that with poor air tightness, and the difference becomes larger as the energy recovery efficiency increases.

5) In most climate zones in China, the equivalent COP can reach 4.0 and 5.0 in heating season and cooling season respectively, which is competitive compared to typical air sourced air conditioning equipment.

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