Based on the simulation results of the typical rural ultra-low energy building (ULEB) in 5 different climatic regions of China, three indicative technical parameters for paralleled-loop exhaust air heat pump (PEAHP) R&D—which are nominal heating/cooling capacity, maximum required fresh air to return air ratio (MFRR) and system energy efficiency grades—were calculated and summarized according to the demand of indoor thermal comforts by using statistic method. The nominal heating/cooling capacities were determined according to the peak loads, which are 6.84/2.01kW, 5.296 kW, 3.9/4.6 kW, 3.08/5.02 kW and 3.4/0.46 kW in the ULEB of Harbin, Beijing, Shanghai, Guangzhou and Kunming respectively. To ensure both thermal comforts and energy conservation, during the heating season, full fresh air supply is suggested in Beijing and the 1:0.5 MFRR is suggested in Harbin, Shanghai, Guangzhou and Kunming. During the cooling season, the 1:5 MFRR is suggested in Shanghai and Guangzhou, the 1:3, 1:1.5 and 1:0.5 MFRR are suggested in Harbin, Beijing and Kunming respectively. The PEAHP energy efficiency grades 1~5 are 7.92~11.7, 7.58~11.5, 7.5~11.35, 6.12~9.27 and 4.64~7.03 during the heating season of Harbin, Beijing, Shanghai, Guangzhou and Kunming respectively, and are 2.33~3.54, 3.93~5.96, 4.61~6.98, 4.62~6.99 and 2.04~3.1 for the cooling season respectively.

Key words: ultra-low energy building, exhaust air heat pump, nominal cooling capacity, heat recovery

1. Introduction

Green building is firstly put forward by Europe and the US [1], and after the development for more than 30 years, buildings become more energy efficient and achieved nearly zero energy consumption, zero energy consumption, or even generating energy while ensuring thermal comfort [2, 3]. To promote the development of ULEB, many developed countries have published a series of standards and codes that indicated the energy target along with time frame [4-7]. Since China introduced the German passive house concept in 2008, the suitable ULEB technology for China is exploring by considering the local climate and environment, living habits and architectural styles [8]. So far, the ULEB project has been carried out in four climatic regions in China [9].
Generally, ULEBs have good airtightness, to ensure indoor air quality and energy conservation, an efficient heating, ventilation and air-conditioning (HVAC) system is essential for ULEBs. Furthermore, the HVAC system for ULEB varies with the building location (climate and the available energy resource) [10-12]. The ULEBs in Nordic countries have small cooling demand, the main heating systems of ULEBs are district heating, and the combination of heat pump and direct electrical heating [13-15]. Wei W et al. compared the energy and economy of a ground-source heat pump (GSHP) and an air-source heat pump (ASHP) in the ULEBs in US, the results shown that, in warmer climates, the GSHP saved little energy or used more energy than the ASHP [16]. Gaurav Singh et al. compared and assessed four different kinds of air-conditioning configurations for achieving the target of nearly/net zero energy buildings in India, the results show that the target of nearly/net zero-energy building can be achieved through radiant vapor compression-based system with vapor compression - dedicated outdoor air system for hot-dry and composite environment conditions [17, 18]. China has 5 different climate zones, compared with the HVAC system – which combines fresh air ventilation and tube radiators that buried in walls or floor – the integrated heat recovery HVAC system – which contains the function of ventilation, cooling and heating – costs less, occupies less space and is more adaptable in different climatical situations [19]. The integrated combination system of plate heat exchanger/membrane energy exchanger + ASHP for ULEB is common in China in recent years [20]. However, the membrane energy recovery device and the flat plate heat recovery device occupy large indoor space, and the maintenance cost of membrane energy exchanger is high [21-24]. The exhaust air heat pump (EAHP) avoids these problems with the complete separation of fresh air and exhaust air, moreover, it occupies less space, easy to maintain [25], and adapt well in different situations [26]. The 75%~300% temperature effectiveness of exhaust heat recovery is the significant characteristic that can’t be observed on other types of heat recovery devices [27]. To further improve the energy efficiency of EAHP, Zhang et al. [28] proposed a multi-heat exchanger EAHP, the study shows that the proposed system can keep both evaporators frost-free, and the heating COP achieved 4.8 at ambient temperature 7 °C/6 °C. The multi-loop heat pump cycle proposed by Lei W avoids the heat and mass exchange of refrigerant between different loops, and has been proved that the COP of multi-loop heat pump is 23.1% higher than conventional single loop heat pump [29]. Xiao et al. [30] studied the working properties of parallel-loop EAHP (PEAHP) under different air supply modes, the results show that the peak COP reached 10.18 when the fresh-air-to-return-air ratio is 1:1. Given that the PEAHP system has good utilization potential in ULEB, the technical requirement characteristics of PEAHP applying in ULEBs of different climate zones should be studied. However, there is no study focus on the application of PEAHP in ULEBs, and the discussions about the ULEBs often focus on single climatic region. Thus, the ULEBs are modelled in 5 climatic regions in China – severe cold zone, cold zone, hot-summer and cold-winter zone, and hot-summer and warm-winter zone. Based on the load on demand side, 3 indicative technical parameters, which are nominal heating/cooling capacity, maximum required fresh air to return air ratio (MFRR) and system energy efficiency grades – are calculated and summarized according to the demand of indoor thermal comforts by using statistic method and thermodynamic cycle analysis. The study outputs typical load characteristics of ULEBs in different climate zones, and the load characteristics were transformed to design principles of PEAHP systems. Thus, the PEAHP system could be designed with targeted principles.
2. Simulation and verification

2.1. Building simulation

As architectural plan shown in Fig.1, the building inner area is 108m$^2$, the story height is 2.8m and the building is south oriented. The envelope heat transfer coefficients are got by the material selection and settings. The envelope thermal parameters and the settings of occupants, equipment and lights in different rooms are comply with the national standard GBT 51350-2019 [31], the detailed envelop materials, the setting of different rooms and building parameters are listed in Tables 1, 2 and 3. DeST is chosen as the simulation software, which adopts multi-region building heat balance theory that based on state-space method. The humidity load is converted to cooling load in the simulation. DeST has been widely used in the architectural research, design and renovation of large commercial buildings including the Chinese National Grand Theater, CCTV, and PLA General Hospital [32]. The simulation is carried out after the settings of structure, envelopre and rooms. As excessive fresh air brings negative effect to energy-saving during heating and cooling season, the required fresh air volume flow rate is set as 300 m$^3$/h according to the requirement of indoor air quality. The calculation are as follows [33]:

$$L_{Fv} = F \times H \times n_v$$  \hfill (1)

![Residential building plan](image1)

(a) Standard floor of the residential building  \hspace{1cm}  (b) 3D model of the residential building

Fig. 1 Residential building plan

<table>
<thead>
<tr>
<th>Table 1. Envelope materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>envelope</td>
</tr>
<tr>
<td>wall</td>
</tr>
<tr>
<td>roof</td>
</tr>
<tr>
<td>Harbin</td>
</tr>
<tr>
<td>Beijing</td>
</tr>
<tr>
<td>windows</td>
</tr>
<tr>
<td>Guangzhou</td>
</tr>
<tr>
<td>Kunming</td>
</tr>
</tbody>
</table>


### Table 2. Thermal settings of occupants, equipment and lights in different rooms [31]

<table>
<thead>
<tr>
<th>Room type</th>
<th>Occupancy ratio</th>
<th>Equipment power density [W/m$^2$]</th>
<th>Capacity utilization</th>
<th>Lighting power density [W/m$^2$]</th>
<th>Lighting duration [h/month]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>19.5%</td>
<td>5</td>
<td>39.4%</td>
<td>6</td>
<td>180</td>
</tr>
<tr>
<td>Bed room</td>
<td>35.4%</td>
<td>6</td>
<td>19.6%</td>
<td>6</td>
<td>180</td>
</tr>
<tr>
<td>Kitchen</td>
<td>4.2%</td>
<td>24</td>
<td>16.7%</td>
<td>6</td>
<td>180</td>
</tr>
<tr>
<td>Toilet</td>
<td>16.7%</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>180</td>
</tr>
<tr>
<td>Staircase</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 3. Thermal parameters of envelope in 5 climatic zones

<table>
<thead>
<tr>
<th>Envelope</th>
<th>Severe cold zone</th>
<th>Harbin ULEB</th>
<th>Cold zone</th>
<th>Beijing ULEB</th>
<th>Hot-summer and cold-winter zone</th>
<th>Shanghai ULEB</th>
<th>Hot-summer and warm-winter zone</th>
<th>Guangzhou ULEB</th>
<th>Mild zone</th>
<th>Kunming ULEB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>0.1–0.15</td>
<td>0.136</td>
<td>0.15–0.2</td>
<td>0.2</td>
<td>0.15–0.40</td>
<td>0.322</td>
<td>0.3–0.8</td>
<td>0.462</td>
<td>0.2–0.8</td>
<td>0.462</td>
</tr>
<tr>
<td>Roof</td>
<td>0.1–0.15</td>
<td>0.143</td>
<td>0.1–0.2</td>
<td>0.2</td>
<td>0.15–0.35</td>
<td>0.293</td>
<td>0.25–0.4</td>
<td>0.347</td>
<td>0.2–0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Ground</td>
<td>0.15–0.3</td>
<td>0.221</td>
<td>0.2–0.4</td>
<td>0.396</td>
<td>-</td>
<td>0.396</td>
<td>-</td>
<td>0.396</td>
<td>-</td>
<td>0.396</td>
</tr>
<tr>
<td>Window</td>
<td>≤1</td>
<td>0.7</td>
<td>≤1.2</td>
<td>1.2</td>
<td>≤2.0</td>
<td>1.7</td>
<td>≤2.5</td>
<td>2.5</td>
<td>≤2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Floor</td>
<td>0.15–0.3</td>
<td>0.234</td>
<td>0.2–0.4</td>
<td>0.396</td>
<td>-</td>
<td>0.396</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>0.4</td>
</tr>
</tbody>
</table>

#### window-wall ratio

<table>
<thead>
<tr>
<th>Southward</th>
<th>Northward</th>
<th>Eastward</th>
<th>Westward</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

#### 2.2. Verification

The ULEB space heating/cooling load results by simulation and theoretical calculation under the design condition without exhaust air recovery based on the state-space method and steady state method in winter conditions and the cooling load factor method in summer conditions, respectively, are compared to ensure the model accuracy. The equation 2–6, 11–12 comply with the equations in reference [34]. Because the ULEB has low energy load with well performing envelope, the solar heat gain through window and the internal heat gain have to be considered other than that in the conventional building. The solar heat gain (eq.10) and internal heat gain (eq.7~9) [35] are considered based on steady state method. The solar radiation is using the average value in the coldest month.D

\[
Q_H = Q_{H,Wa} + Q_{H,Win} + Q_{H,Rf} + Q_{H,G} + Q_{Air} - Q_m - Q_{Liq} - Q_{Ep} - Q_{SHG}
\]  
(2)

\[
Q_C = Q_{C,Wa} + Q_{C,Rf} + Q_{C,Win} + Q_{C,Win,SHG} + Q_m + Q_{Liq} + Q_{Ep} + Q_{Fre}
\]  
(3)

$H$ is the flux through envelope in winter.
\[ Q_{H,Wa/Wal/Rf/G} = K_{Wal/Rf}/G A_{Wal/Rf}/G (t_R - t_{O,H}) \]  

(4)

Cooling load caused by heat transfer of envelop:

\[ Q_{C,Wal/Rf} = K_{Wal/Rf} A_{Wal/Rf} (t_{Wal/Rf,(N/S/W/E)},c(t) - t_R) \]  

(5)

\[ Q_{C,Wal,SHG} = C_a A_{Wal,(N/S/W/E)} C_s C_r D_f(N/S/W/E)_{max} C_{LQ(N/S/W/E)} \]  

(6)

Occupants heat gain:

\[ Q_m = q_m k_1 \]  

(7)

Lighting heat gain:

\[ Q_{Lig} = F q_{Lig} k_2 k_3 \]  

(8)

Equipment heat gain:

\[ Q_{Ep} = F q_{Ep} k_4 k_5 \]  

(9)

Solar heat gain through windows [35]:

\[ Q_{SHG} = SHGC - E_{D} A_{Wa} \]  

(10)

Heating load caused by fresh air ventilation and infiltration:

\[ Q_{Air} = [L_p \rho (h_R - h_O) + L_{Freek} \rho (h_R - h_O)] / 3.6 \]  

(11)

Cooling load caused by fresh air ventilation:

\[ Q_{Fre} = L_{Freek} \rho_{av} (h_O - h_R) / 3.6 \]  

(12)

As shown in Fig.2, under the design condition, the theoretical calculation results are always higher than the simulation results, because the heat storage in envelope is ignored in the calculations. While the differences between them are mostly remain in 10% and this comparison supports the reliability of the ULEB models in the five cities.

![Fig. 2 The load of theoretical calculation and simulation](image)

3. System description

Fig.3 shows the innovative PEAHP system configuration. The solid arrow in Fig.3 indicates the refrigerant flow direction in winter test conditions, and the dotted arrow indicates the refrigerant flow direction in summer test conditions. The heat pump loop connected with compressor A is loop A, and the heat pump loop connected with compressor B is loop B. As shown in Fig.3, in winter, the cold fresh air mixes with the return air and then is firstly preheated by passing through the No.1 condenser, then the total air is reheated to supply air in the second loop, and supplied to room lastly, while the heat of the warm exhaust air is firstly recovered by the No.4 evaporator and then is recovered for the
second time by the No.3 evaporator. The same principle applies to summer conditions. Fig.4 shows the PEAHP cycle in p-h diagram which take R410A as the refrigerant, the PEAHP system divided the working temperature and pressure intervals into high-pressure loop and low-pressure loop, which avoided all compressors from working under the most severe conditions to prevent overly lowering the circulation mass flow rate.

![Fig. 3 Innovative PEAHP system configuration](image1)

![Fig. 4 PEAHP cycle in p-h diagram using R410A](image2)

4. Results and discussion

Based on the load on demand side and ambient temperature in different climatic regions, the technical requirements of PEAHP system are calculated, analyzed and summarized to support further research and development. Because the PEAHP integrated with the functions of heat recovery, ventilation, cooling and heating, the system is considered as the indoor environment control system to operate in the whole year (8760h).

4.1. Nominal heating/cooling capacity

Fig.5 shows the annual heating/cooling consumption and peak load of ULEBs at different exhaust air energy recovery efficiency in 5 climatic regions. The exhaust air energy recovery efficiency is:

$$\eta = \frac{h_{\text{outlet}} - h_0}{h_r - h_0}$$  \hspace{1cm} (13)

As heating and cooling function are integrated in PEAHP system, it is essential to determine the nominal heating/cooling capacity of PEAHP system based on peak heating/cooling load, the peak heating/cooling loads are determined as the maximum loads when 3% time (hours) is unmet in the whole heating/cooling season of the 5 climatical regions [36]. Compared to conventional building, even though the thermal performance and air tightness of envelope for ULEB has been improved, there is an obvious energy load shifting from heating load to cooling load as the location changed from severe cold zone, to cold zone, to hot-summer and cold-winter zone and to hot-summer and warm
winter zone, which is consistent with the results of the previous studies [37]. With the decline of energy recovery efficiency, Fig. 5 shows an obvious rise of annual heating consumption in Harbin, Beijing and Shanghai, while annual cooling consumptions are almost remain unchanged.

As an indirect heat recovery device, the PEAHP could bear the total space heating/cooling load caused by envelope heat loss and ventilation, so the peak load without exhaust air recovery, namely the case with 0% exhaust air energy recovery efficiency, is the baseline to determine the nominal heating/cooling capacity of PEAHP system. The changing trend of energy load and peak load is correlated with the climate characteristics of each zone China. The ULEB in Harbin has higher heating requirements, while it requires more for cooling in Guangzhou. The differences of peak heating load and peak cooling load in Harbin and Guangzhou are 4.84 kW and 2.06 kW respectively. The difference of the annual heating consumption to cooling consumption ratio between the BJ75% ULEB and the building in reference [38] is only 2.46%. The PEAHP should be heating capacity dominated in Harbin, Beijing and Kunming, the nominal heating capacity should reach 6.84kW, 5kW and 3.4kW respectively. And the PEAHP should be cooling capacity dominated in Shanghai and Guangzhou, the nominal cooling capacity should reach 4.6kW and 5.02kW respectively.

![Fig. 5 Annual heating/cooling consumption and peak load in different exhaust air energy recovery efficiency](image)

4.2. Maximum required fresh air to return air ratio (MFRR)

Given that the indoor and outdoor temperature difference in winter is much great in the most cities in China, for instance, the design outdoor temperature for heating in Beijing is -9.9°C, and the temperature difference between indoor and outdoor approaches 30°C, especially for the ULEBs, the heat loss caused by ventilation accounts for a high percentage in total building energy consumption [39]. Based on the required fresh air volume and energy saving, the ventilation rate is fixed as 300 m³/h. Indoor temperature is regulated by temperature and volume flow rate of supply air. If supply air is totally fresh air, especially under the extreme outdoor condition, although small air volume results in less fan energy consumption, the required supply air temperature to cover space heating/cooling load will be extremely low or high, and the large temperature difference between supply air and indoor air sacrifices the somatosensory comfort. Instead, if increasing the supply air volume by gradually adding return air volume, the suitable comfort is at the expense of fan energy consumption. Thus,
when the return air should be added, and how much volume should be added, these problems should be studied. This section determined the MFRR by studying the interaction of fresh air to return air ratio (FRR) and required supply air temperature for covering space heating/cooling load. Fig.6 shows the whole year time distribution of different required supply air temperature under different FRR during heating and cooling seasons in 5 climatic regions. The time percentages are labeled on the corresponding bars, the percentages of unlabeled bars are fewer than 3%. Full fresh air means supply air is totally fresh air, fresh air/return air 1:n means the required fresh air is mixed with a n times volume of return air before going through heat exchanger. In order to cover the space heating/cooling load by supply air, the supply air has to be heated or cooled to have a large temperature difference with indoor air, as the required fresh air flow rate is merely 300m³/h. Required supply air temperature range is divided into weak heating part ($T_{sup}$ ≤36°C), strong heating part (36°C < $T_{sup}$ ≤41°C) and extreme heating part ($T_{sup}$ > 41°C). The temperature range of weak heating is $T_{sup}$ ≤36°C instead of 20°C ≤$T_{sup}$ ≤36°C, it is due to the fact that the load caused by fresh air is included in the total load during simulation, sometimes no heating load generates even the required supply air temperature is below 20°C. The indoor temperature still be maintained at a comfortable temperature range of 20 ~ 26°C. So the temperature range of weak heating is divided as $T_{sup}$ ≤36°C, the required supply air temperature dividing for cooling is the same causality.

Large air supply volume is not conducive to system energy saving. Therefore, return air volume flow rate increases gradually at the increment of 150 m³/h to reduce extreme heating/cooling period within 3%. 3%The calculation process of required supply air temperature at the 1:n ratio of fresh air to return air shown as the follows (the value of heating load is positive, the value of cooling load is negative):

The temperature of mixed air (mix of fresh air and return air, the $\rho$ and $c_p$ of fresh air and return are considered the same) is:

$$t_M = \frac{t_0 + nt_R}{1 + n}$$  \hspace{1cm} (11)

The total space heating/cooling load is:

$$Q_t = \rho c_p Q_{v, sup} (t_{sup} - t_M) / 3600$$  \hspace{1cm} (12)

So the required supply air temperature is calculated by:

$$t_{sup} = \frac{t_0 + nt_R + \frac{3600Q_{H/C}}{c_p\rho Q_{v, sup}}}{1 + n}$$  \hspace{1cm} (13)

For ULEBs, as shown in Eq.(13), the hourly required supply air temperature is positively correlated with outdoor temperature and heating/cooling load at fixed FRR. Under the condition of full fresh air supplying, as the average outdoor temperature rises and the heating load decreases in the sequence of Harbin, Beijing, Shanghai and Guangzhou, the extreme heating period first declines and then increases. The extreme heating period of Kunming is longer than that of Shanghai, even the average outdoor temperature of the former is higher than the latter during winter. This is because the ULEB in Kunming require less insulation than in other climate zones, when having the same ambient temperature, the building in Kunming has higher peak heating load than other locations. What’s more, the higher average outdoor temperature in winter of Kunming rises the inlet air temperature of condenser, which also leads to higher supply air temperature. Meanwhile, as the average outdoor temperature rises and the cooling load increases in the sequence of Harbin, Beijing, Shanghai and Guangzhou, the extreme cooling period first declines and then increases similarly. Large temperature
difference between interior and exterior makes the required return air volume in heating season is lower than that in cooling season. The lower cooling load in Kunming results in the lower requirements of return air. During the heating season, full fresh air supply is suggested in Beijing and the 1:0.5 MFRR is suggested in Harbin, Shanghai, Guangzhou and Kunming. During the cooling season, the 1:5 MFRR is suggested in Shanghai and Guangzhou, the 1:3, 1:1.5 and 1:0.5 MFRR are suggested in Harbin, Beijing and Kunming respectively.

![Fig. 6 Time distribution of different required supply air temperature](image)

(a) Heating  
(b) Cooling

### 4.3. PEAHP system energy efficiency grade

The national standard GB 21455-2019 gives the energy efficiency level of conventional heat pump [40]. Till now, there is no standards nor codes for the energy efficiency of PEAHP system. This section takes the conventional combination system of membrane energy exchanger (75% enthalpy effectiveness) and heat pump as a reference to calculate the system energy efficiency grade under the same energy consumption when the heating and cooling capacity able to meet the space heating/cooling load. The calculation results can be used as the technical guidance for the innovation and optimization of PEAHP system and the development of relevant standards. The calculation process is shown as follows:

\[
\frac{Q_{CV.H}}{APF_{CV.H}} = \frac{Q_{PEAHP.H}}{HSPF_{PEAHP.H}} \quad (14)
\]

\[
\frac{Q_{CV.C}}{APF_{CV.C}} = \frac{Q_{PEAHP.C}}{CSPF_{PEAHP.C}} \quad (15)
\]

\[
Q_{CV.H} = Q_{CV.B,H} + Q_{Fe,H} \quad (16)
\]

\[
Q_{PEAHP.H} = Q_{PEAHP.B,H} + Q_{Fe,H} \quad (17)
\]

\[
Q_{CV.C} = Q_{CV.B,C} + Q_{Fe,C} \quad (18)
\]
Fig. 7 shows the energy efficiency grades for PEAHP system. GB 21455-2019 specifies the energy efficiency grades by annual performance factors. While the HSPF and CSPF values are used to evaluate the energy efficiency grades for PEAHP system. As Wang L [41] has studied EAHP system at an ambient temperature of -5°C and 40°C, and the system coefficient of performance is 10.25 and 4.7 respectively. So the energy efficiency grades in Fig. 7 are realizable. As Fig. 7(a) shown, the PEAHP system applied in harsh winter should have a higher energy efficiency. The PEAHP system energy efficiency grades for Beijing and Shanghai are similar, the average difference between them is only 0.118. During the cooling season, shown in Fig. 7(b), the energy efficient is much higher at the city which has higher average ambient temperature. The PEAHP system energy efficiency grades for Shanghai and Guangzhou are almost the same, the average difference between them is only 0.016. The minimum allowable energy efficiency grade 1~5 for Harbin, Beijing, Shanghai, Guangzhou and Kunming PEAHP systems are 7.92~11.7, 7.58~11.5, 7.5~11.35, 6.12~9.27 and 4.64~7.03 respectively in heating season, and 2.33~3.54, 3.93~5.96, 4.61~6.98, 4.62~6.99 and 2.04~3.1 respectively in cooling season. As the energy efficiency grades of the PEAHP system in Kunming are close to each other, this 5 energy efficiency grades can be packaged into one grade.

5. Conclusions

This paper modeled ULEBs in 5 climatic regions in China and proposes an innovative PEAHP system. Based on the demand of indoor thermal comfort, 3 indicative technical parameters of PEAHP system are calculated and summarized by using the statistic method and thermodynamic cycle analysis. The parameters are nominal heating/cooling capacity, maximum required fresh air to return air ratio (MFRR) and system energy efficiency grades. The purpose of this study is to provide indicative technical principles for the R&D of PEAHP system. Conclusions are as follows:

(1) In the order of severe cold zone, cold zone, hot-summer and cold-winter zone, hot-summer and warm winter zone, an obvious shifting from heating load dominance to cooling load dominance is observed. And peak heating load reduces and peak cooling load rises in sequence.
With the decline of heat recovery efficiency, the annual heat consumption rises obviously and cooling consumptions almost keep constant in Harbin, Beijing and Shanghai.

During the heating season, full fresh air supply is suggested in Beijing and the 1:0.5 MFRR is suggested in Harbin, Shanghai, Guangzhou and Kunming. During the cooling season, the 1:5 MFRR is suggested in Shanghai and Guangzhou, the 1:3, 1:1.5 and 1:0.5 MFRR are suggested in Harbin, Beijing and Kunming respectively.

The energy efficiency grade 1~5 for Harbin, Beijing, Shanghai, Guangzhou and Kunming PEAHP systems are 7.92~11.7, 7.58~11.5, 7.5~11.35, 6.12~9.27 and 4.64~7.03 respectively in heating season, and 2.33~3.54, 3.93~5.96, 4.61~6.98, 4.62~6.99 and 2.04~3.1 respectively in cooling season.

Acknowledgement

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Nomenclature

\[
\begin{align*}
Q_H & \quad \text{heating load [W]} \\
Q_{Lig} & \quad \text{lighting heat gain [W]} \\
Q_m & \quad \text{occupants heat gain [W]} \\
Q_{SHG} & \quad \text{solar heat gain [W]} \\
Q_{V, \text{sup}} & \quad \text{supply air volume flow rate [m³/h]} \\
Q_{\text{Win,SHG}} & \quad \text{cooling load caused by window heat transfer [W]} \\
q_m & \quad \text{occupants heat dissipation [W]} \\
q_{Lig} & \quad \text{lighting power density [W/m}^2]\text{]} \\
q_{\text{Ep}} & \quad \text{equipment power density [W/m}^2]\text{]} \\
\eta & \quad \text{energy recovery efficiency} \\
\rho_{ao} & \quad \text{air density [kg/ m}^3]\text{]}
\end{align*}
\]

\[
\begin{align*}
A & \quad \text{area of envelop [m}^2]\text{]} \\
APF & \quad \text{annual performance factor} \\
CSPF & \quad \text{cooling seasonal performance factor} \\
C_a & \quad \text{effective area factor} \\
C_s & \quad \text{shading coefficient of window panes} \\
C_i & \quad \text{shading coefficient of indoor shading facilities} \\
C_{LQ} & \quad \text{cooling load factor} \\
c_p & \quad \text{specific heat of air [J/(kg\,\cdot\,K)]} \\
D_{j,max} & \quad \text{maximum solar heat factor [W/m}^2]\text{]} \\
E_D & \quad \text{Solar radiation intensity [W/m}^2]\text{]} \\
F & \quad \text{living area [m}^2]\text{]} \\
H & \quad \text{height [m]} \\
HSPF & \quad \text{heating seasonal performance factor} \\
\h & \quad \text{enthalpy [kJ/kg]} \\
K & \quad \text{heat transfer coefficient [W/(m}^2\,\cdot\,K)]} \\
k_1 & \quad \text{occupancy ratio} \\
k_2 & \quad \text{utilization rate of lights} \\
k_3 & \quad \text{electrothermal conversion rate of light}
\end{align*}
\]

\[
\begin{align*}
\text{Latin letters} & \\
\text{Greek letters} & \\
\text{Subscripts} & \\
B & \quad \text{building} \\
C & \quad \text{cooling} \\
G & \quad \text{ground} \\
H & \quad \text{heating}
\end{align*}
\]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>$k_4$</td>
<td>capacity utilization</td>
</tr>
<tr>
<td>$k_5$</td>
<td>electrothermal conversion rate of equipment</td>
</tr>
<tr>
<td>$L_p$</td>
<td>penetration air volume flow rate [m$^3$/h]</td>
</tr>
<tr>
<td>$L_{Fre}$</td>
<td>fresh air volume flow rate [m$^3$/h]</td>
</tr>
<tr>
<td>$n_v$</td>
<td>ventilation rate, n=0.5</td>
</tr>
<tr>
<td>$Q_{Air}$</td>
<td>heating load caused by total air [W]</td>
</tr>
<tr>
<td>$Q_c$</td>
<td>cooling load [W]</td>
</tr>
<tr>
<td>$Q_{CV}$</td>
<td>load of the conventional system [W]</td>
</tr>
<tr>
<td>$Q_{Ep}$</td>
<td>equipment heat gain [W]</td>
</tr>
<tr>
<td>$Q_{Fre}$</td>
<td>heating load caused by fresh air [W]</td>
</tr>
</tbody>
</table>

References


[40] GB 21455-2019, Minimum allowable values of the energy efficiency and energy efficiency grades for room air conditioners, Beijing, 2019 (in Chinese)


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