TECHNICAL REQUIREMENTS ANALYSIS OF INTEGRATED PARALLELED-LOOP EXHAUST AIR HEAT PUMP SYSTEM APPLIED TO ULTRA-LOW ENERGY BUILDING IN DIFFERENT CLIMATIC REGIONS OF CHINA

by

Xiaoya JIA, Guoyuan MA*, Feng ZHOU*, Lei WANG, Guoqiang WU, and Shuailing LIU

Department of Refrigeration and Cryogenic Engineeing,
Beijing University of Technology, Beijing, China

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Based on the simulation results of the typical rural ultra-low energy building (ULEB) in five 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 6.84-2.01 kW, 5-2.96 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*: ULEB, exhaust air heat pump, heat recovery, nominal cooling capacity*

Introduction

Green building is firstly put forward by Europe and the USA [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].

* Corresponding authors, e-mail: magy@bjut.edu.cn; zhoufeng@bjut.edu.cn

Generally, ULEB have good airtightness, to ensure indoor air quality and energy conservation, an efficient HVAC system is essential for ULEB. Furthermore, the HVAC system for ULEB varies with the building location (climate and the available energy resource) [10-12]. The ULEB in Nordic countries have small cooling demand, the main heating systems of ULEB are district heating, and the combination of heat pump and direct electrical heating [13-15]. Wu *et al.* [16] compared the energy and economy of a ground-source heat pump (GSHP) and an air-source heat pump (ASHP) in the ULEB in USA, the results shown that, in warmer climates, the GSHP saved little energy or used more energy than the ASHP. Singh and Das [17, 18] 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. China has five 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 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 Wang *et al*. [29] 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. Xiao *et al.* [30] studied the working properties of 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 ULEB of different climate zones should be studied. However, there is no study focus on the application of PEAHP in ULEB, and the discussions about the ULEB often focus on single climatical region. Thus, the ULEB are modelled in five 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, three indicative technical parameters, which are nominal heating-cooling capacity, 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 ULEB 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.

Simulation and verification

Building simulation

As architectural plan shown in fig. 1, the building inner area is 108 m^2, the story height is 2.8 m 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 tabs. 1-3. The 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. The 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 cared out after the settings of structure, envelope 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 per hour according to the requirement of indoor air quality. The calculation are [33]:

$$L_{\mathrm{fre}} = F \times H \times n_v \tag{1}$$

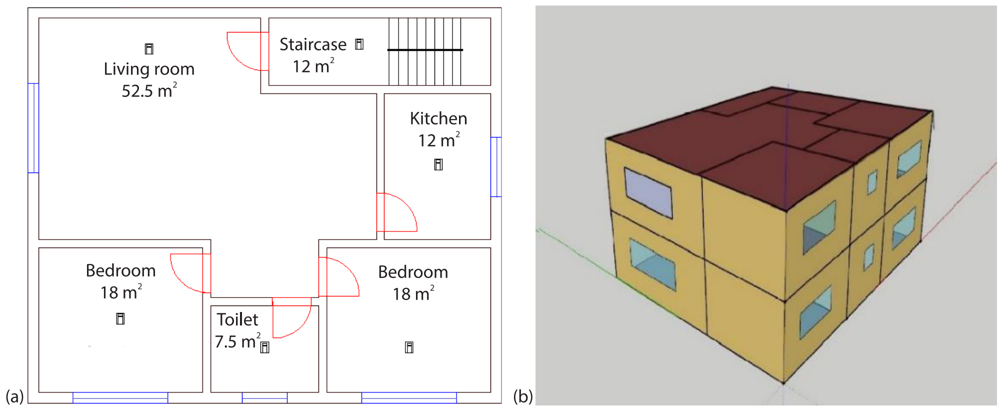

Figure 1. Residential building plan; (a) standard floor of the residential building and (b) 3-D model of the residential building verification

Table 1. Envelope materials

Envelope	Material	
Wall	Concrete / polystyrene board / cement mortar	
Roof	Concrete / extruded polystyrene board / water proof roll	
Windows	Harbin	Coated treble glazed window
	Beijing	Coated treble glazed window
	Shanghai	Low-E double glazed window
	Guangzhou	Single glass window
	Kunming	Single glass window

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

Room type	Occupancy ratio	Equipment power density [Wm^{-2}]	Capacity utilization	Lighting power density [Wm^{-2}]	Lighting duration [hour per month]
Living room	19.5%	5	39.4%	6	180
Bed room	35.4%	6	19.6%	6	180
Kitchen	4.2%	24	16.7%	6	180
Toilet	16.7%	0	0	6	180
Staircase	0	0	0	0	0

Table 3. Thermal parameters of envelope in five climatic zones

Envelope	Heat transfer coefficient [W/(m²•K)]									
	Severe cold zone	Harbin ULEB	Cold zone	Beijing ULEB	Hot-summer and cold-winter zone	Shanghai ULEB	Hot-summer and warm-winter zone	Guangzhou ULEB	Mild zone	Kunming ULEB
Wall	0.1~0.15	0.136	0.15~0.2	0.2	0.15~0.40	0.322	0.3~0.8	0.462	0.2~0.8	0.462
Roof	0.1~0.15	0.143	0.1~0.2	0.2	0.15~0.35	0.293	0.25~0.4	0.347	0.2~0.4	0.4
Ground	0.15~0.3	0.221	0.2~0.4	0.396	-	0.396	-	0.396	-	0.396
Window	≤ 1	0.7	≤ 1.2	1.2	≤ 2.0	1.7	≤ 2.5	2.5	≤ 2.0	1.8
Floor	0.15~0.3	0.234	0.2~0.4	0.396	-	0.396	-	0.4	-	0.4

Window-wall ratio			
Southward	Northward	Eastward	Westward
0.3	0	0.15	0.15

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 eqs. (2)-(6), (11) and (12) comply with the equations in [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, eqs. (7)-(9) [35] are considered based on steady-state method. The solar radiation is using the average value in the coldest month:

$$Q_{\mathrm{H}} = Q_{\mathrm{H,wa}} + Q_{\mathrm{H,win}} + Q_{\mathrm{H,Rf}} + Q_{\mathrm{H,G}} + Q_{\mathrm{air}} - Q_{\mathrm{m}} - Q_{\mathrm{lig}} - Q_{\mathrm{ep}} - Q_{\mathrm{SHG}} \tag{2}$$

$$Q_{\mathrm{C}} = Q_{\mathrm{C,wa}} + Q_{\mathrm{C,Rf}} + Q_{\mathrm{C,win}} + Q_{\mathrm{C,win,SHG}} + Q_{\mathrm{m}} + Q_{\mathrm{lig}} + Q_{\mathrm{ep}} + Q_{\mathrm{fre}} \tag{3}$$

Heat flux through envelope in winter:

$$Q_{\mathrm{H,wa/win/Rf/G}} = K_{\mathrm{wa/win/Rf/G}} A_{\mathrm{wa/win/Rf/G}} (t_{\mathrm{R}} - t_{\mathrm{O,H}}) \tag{4}$$

Coolong load caused by heat transfer of envelop:

$$Q_{\mathrm{C,wa/Rf}} = K_{\mathrm{wa/Rf}} A_{\mathrm{wa/Rf}} (t_{c(\tau),\mathrm{wa/Rf(N/S/W/E)}} - t_{\mathrm{R}}) \tag{5}$$

$$Q_{\mathrm{C,win,SHG}} = C_{\mathrm{a}} A_{\mathrm{win(N/S/W/E)}} C_{\mathrm{s}} C_{\mathrm{i}} D_{j_{\max},\mathrm{(N/S/W/E)}} C_{\mathrm{LQ,(N/S/W/E)}} \tag{6}$$

Occupants heat gain:

$$Q_{\mathrm{m}} = q_{\mathrm{m}} k_1 \tag{7}$$

Lighting heat gain:

$$Q_{\mathrm{lig}} = F q_{\mathrm{lig}} k_2 k_3 \tag{8}$$

Equipment heat gain:

$$Q_{\mathrm{ep}} = F q_{\mathrm{ep}} k_4 k_5 \tag{9}$$

Solar heat gain trough windows [35]:

$$Q_{\mathrm{SHG}} = \mathrm{SHGC} \times E_D A_{\mathrm{win}} \tag{10}$$

Heating load caused by fresh air ventilation:

$$Q_{\mathrm{air}} = \frac{L_p \rho (h_{\mathrm{R}} - h_{\mathrm{O}}) + L_{\mathrm{fre}} \rho (h_{\mathrm{R}} - h_{\mathrm{O}})}{3.6} \tag{11}$$

Colling load caused by fresh air ventilation:

$$Q_{\mathrm{fre}} = \frac{L_{\mathrm{fre}} \rho_{\mathrm{ao}} (h_{\mathrm{O}} - h_{\mathrm{R}})}{3.6} \tag{12}$$

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 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.

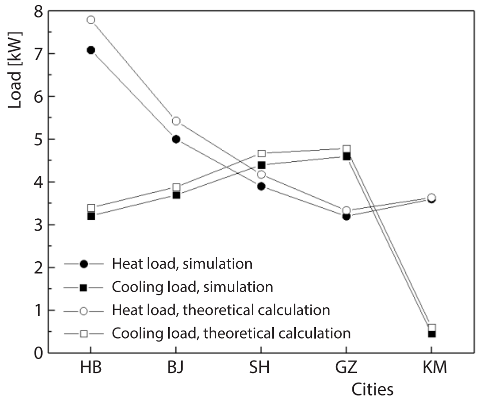

Figure 2. The load of theoretical calculation and simulation

System description

Figure 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. Figure 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

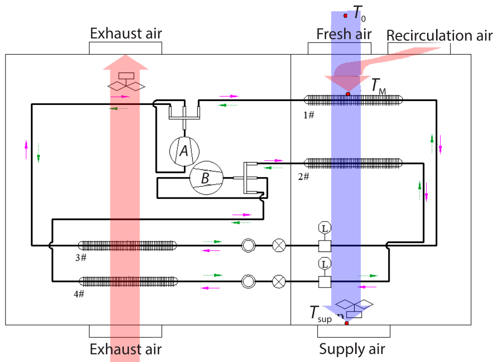

Figure 3. Innovative PEAHP system configuration

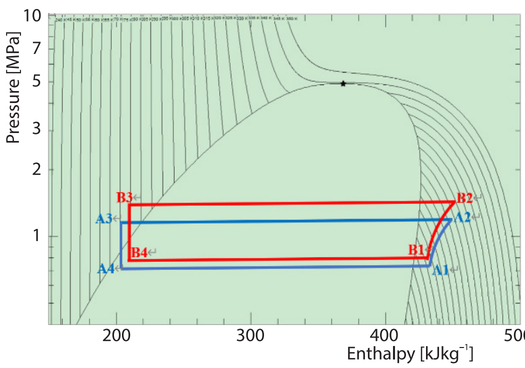

Figure 4. The PEAHP cycle in *p-h* diagram using R410A

pressure loop, which avoided all compressors from working under the most severe conditions to prevent overly lowering the circulation mass-flow rate.

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 (8760 hours).

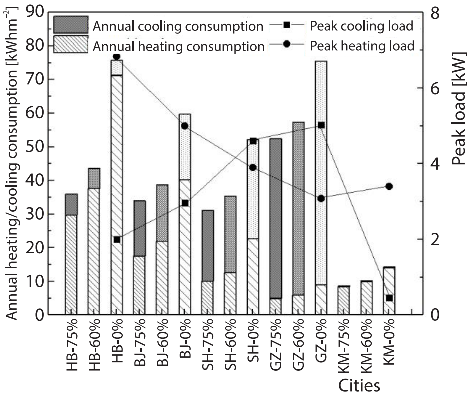

Figure 5. Annual heating-cooling consumption and peak load in different exhaust air energy recovery efficiency

Nominal heating-cooling capacity

Figure 5 shows the annual heating-cooling consumption and peak load of ULEB at different exhaust air energy recovery efficiency in five climatic regions. The exhaust air energy recovery efficiency is:

$$\eta = \frac{h_{\text{outlet}} - h_{\text{O}}}{h_{\text{R}} - h_{\text{O}}} \tag{13}$$

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 five 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 cooling consumption ratio between the BJ75% ULEB and the building in [38] is only 2.46%. The PEAHP should be heating capacity dominated in Harbin, Beijing, and Kunming, the nominal heating capacity should reach 6.84 kW, 5 kW, and 3.4 kW, respectively. The PEAHP should be cooling capacity dominated in Shanghai and Guangzhou, the nominal cooling capacity should reach 4.6 kW and 5.02 kW, respectively.

Maximum required fresh air to return air ratio

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 ULEB, 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 m^3 per hour. 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 five 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 300 m^3 per hours. Required supply air temperature range is divided into weak heating part ($T_{sup} \leq 36$ °C), strong heating part (36 C < $T_{sup} \leq$41 °C) and extreme heating part ($T_{sup} > 41$ °C). The temperature range of weak heating is $T_{sup} \leq 36$ °C instead of 20 °C≤ $T_{sup} \leq 36$ °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 $T_{sup} \leq 36$ °C, the required supply air temperature dividing for cooling is the same causality.

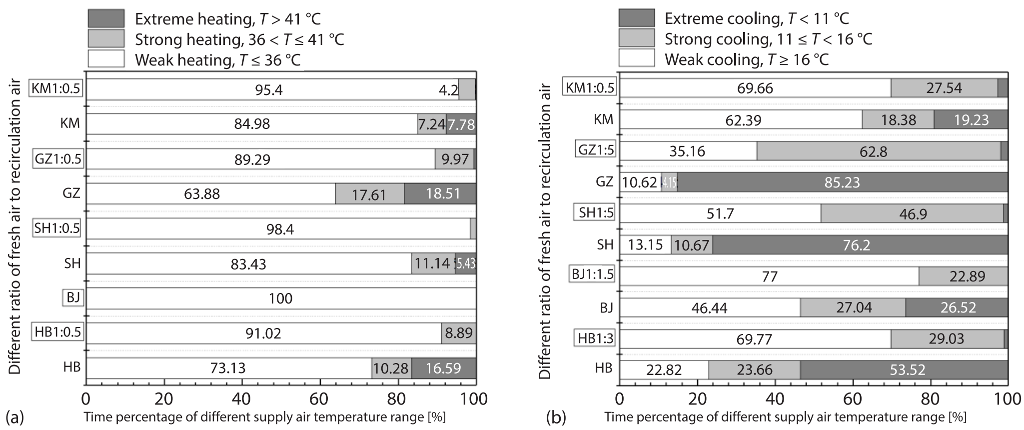

Figure 6. Time distribution of different required supply air temperature; (a) heating and (b) cooling

Large air supply volume is not conducive to system energy saving. Therefore, return air volume flow rate increases gradually at the increment of 150 m^3 per hour to reduce extreme heating-cooling period within 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 ρ and c_p of fresh air and return are considered the same):

$$t_{\mathrm{M}} = \frac{t_{\mathrm{O}} + nt_{\mathrm{R}}}{1+n} \tag{14}$$

The total space heating-cooling load:

$$Q_t = \frac{\rho c_p Q_{V,\mathrm{sup}}(t_{\mathrm{sup}} - t_{\mathrm{M}})}{3600} \tag{15}$$

So the required supply air temperature is calculated:

$$t_{\mathrm{sup}} = \frac{t_{\mathrm{O}} + nt_{\mathrm{R}}}{1+n} + \frac{3600 Q_{\mathrm{H/C}}}{c_p \rho Q_{v,\mathrm{sup}}} \tag{16}$$

For ULEB, as shown in eq. (16), 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.

The 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:

$$\frac{Q_{\mathrm{CV,H}}}{APF_{\mathrm{CV,H}}} = \frac{Q_{\mathrm{PEAHP,H}}}{HSPF_{\mathrm{PEAHOP,H}}} \tag{17}$$

$$\frac{Q_{\text{CV,C}}}{APF_{\text{CV,C}}} = \frac{Q_{\text{PEAHP,C}}}{CSPF_{\text{PEAHP,C}}} \tag{18}$$

$$Q_{\text{CV,H}} = Q_{\text{CV,B,H}} + Q_{\text{fre,H}} \tag{19}$$

$$Q_{\text{PEAHP,H}} = Q_{\text{PEAHP,B,H}} + Q_{\text{fre,H}} \tag{20}$$

$$Q_{\text{CV,C}} = Q_{\text{CV,B,C}} + Q_{\text{fre,C}} \tag{21}$$

$$Q_{\text{PEAHP,C}} = Q_{\text{PEAHP,B,C}} + Q_{\text{fre,C}} \tag{22}$$

Figure 7 shows the energy efficiency grades for PEAHP system. The 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 *et al*. [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 is 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 five energy efficiency grades can be packaged into one grade.

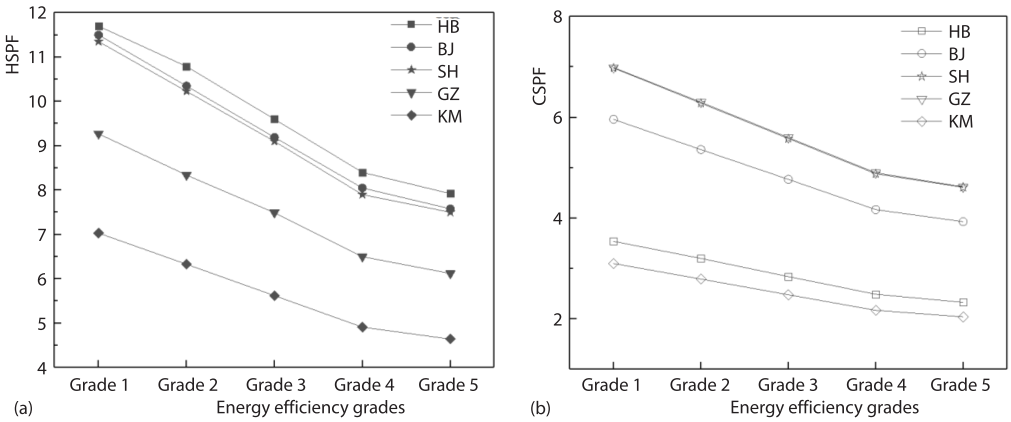

Figure 7. Energy efficiency grades for PEAHP system; (a) HSPF and (b) CSPF

Conclusions

This paper modeled ULEB in five climatic regions in China and proposes an innovative PEAHP system. Based on the demand of indoor thermal comfort, three 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, 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.

- 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 grade1~5 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.

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Nomenclature

A – area of envelop, [m^2]
C_a – effective area factor
C_s – shading coefficient of window panes
C_i – shading coefficient of indoor shading facilities
C_{LQ} – cooling load factor
c_p – specific heat of air, [Jkg^{-1}K^{-1}]
$D_{j,\max}$ – maximum solar heat factor, [Wm^{-2}]
E_D – solar radiation intensity, [Wm^{-2}]
F – living area, [m^2]
H – height [m^2]
h – enthalpy, [kJkg^{-1}]
K – heat transfer coefficient, [Wm^{-2}K^{-1}]
k_1 – occupancy ratio
k_2 – utilization rate of lights
k_3 – electrothermal conversion rate of light
k_4 – capacity utilization
k_5 – electrothermal conversion rate of equipment
L_p – penetration air volume flow rate, [m^3 per hour]
L_{fre} – fresh air volume flow rate, [m^3 per hour]
n_v – ventilation rate, n = 0.5
Q_{air} – heating load caused by total air, [W]
Q_C – cooling load, [W]
Q_{CV} – load of the conventional system, [W]
Q_{ep} – equipment heat gain, [W]
Q_{fre} – heating load caused by fresh air, [W]
Q_H – heating load, [W]
Q_{lig} – lighting heat gain, [W]
Q_m – occupants heat gain, [W]
Q_{SHG} – solar heat gain, [W]
$Q_{V,sup}$ – supply air volume flow rate, [m^3 per hour]
$Q_{win,SHG}$ – cooling load caused by window heat transfer, [W]
q_{ep} – equipment power density, [Wm^{-2}]
q_{lig} – lighting power density, [Wm^{-2}]
q_m – occupants heat dissipation, [W]
t – temperature, [°C]
$t_{c(\tau)}$ – cooling load temperature, [°C]

Greek symbols

η – energy recovery efficiency
ρ_{ao} – air density, [kgm^{-3}]

Subscripts

B – building
C – cooling
G – ground
H – heating
M – mixing of fresh air and return air
O – outdoor
R – room
Rf – roof
sup – supply air
wa – wall
win – window

Acronyms

APF – annual performance factor
CSPF – cooling seasonal performance factor
HSPF – heating seasonal performance factor
SHGC – solar heat gain coefficient

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