Analysis on energy consumption of water-loop heat pump system in China

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Abstract

Annual energy consumption of water-loop heat pump system (WLHPS) and conventional air conditioning system (CACS) is compared and analyzed when they are applied in different representative cities in China, respectively. The results show that, if coal-burning boiler is used as the heat source, the WLHPS does not have any effect of energy saving, but it has distinct effect under appropriate condition if electric boiler is used. Considering the other affecting factors, the system can be applied in most areas in China, especially along the Coast of Yangtze River and its northern parts.
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1. Introduction

Water-loop heat pump system (WLHPS) was first presented in the 1960s [1]. Now it has been applied as a kind of energy saving for centralized air conditioning systems. It is composed of many water source heat pump units linked by a closed water-piping loop. The water in the loop can be thought as a heat source/sink for each of the heat pump units and it can store the heat inside a building and meet the different requirements of cooling and heating of each heat pump unit during a certain time of period. And the heat from the inner zone (interior zone or core area) in the

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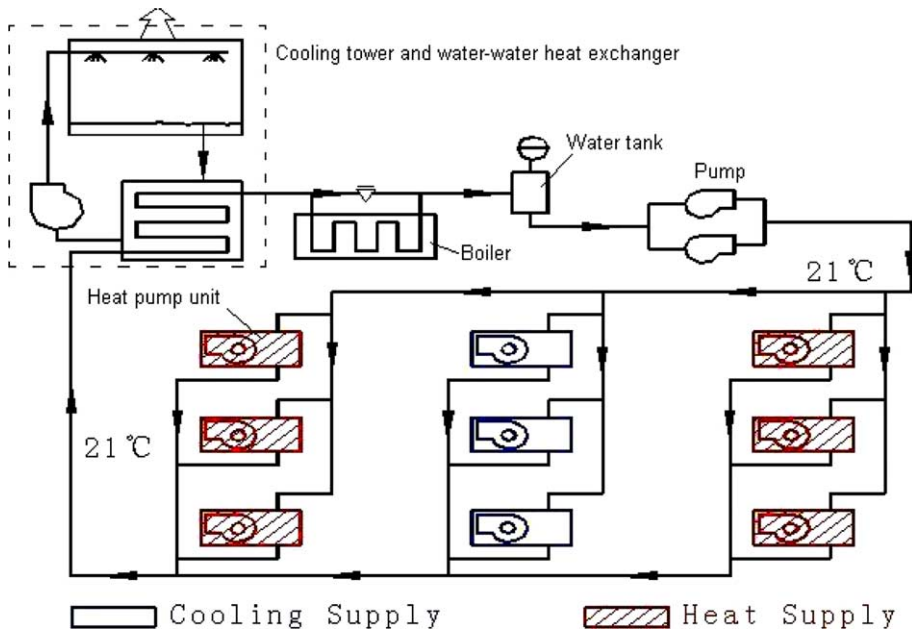 *E-mail address:* zwlian@sjtu.edu.cn (Z. Lian).

Fig. 1. The structure of WLHPS.

building can be transferred to its outer zone (exterior zone or perimeter area) by the circulation water and heat recovery can be realized in this way. The schematic diagram of the structure of the WLHPS is shown in Fig. 1.

The WLHPS has been paid more and more attention as the energy consumption of air conditioning increases since 1990s and has been widely applied in the United States, Japan, etc. [1–5]. It was introduced into China more than 20 years ago and has also been used in some cities but not as many as expected. And there is blindness of its application. It sometimes was not applied in the areas where it should be but, on the contrary, it did in the areas where it should not be. One of the reasons is because of the misunderstanding of it. For example, when the WLHPS considers to be applied in an actual project, the analyses on energy consumption of a whole year are usually neglected. Therefore the affecting factors of operation energy consumption cannot be taken into account and, the effect of energy saving of the WLHPS cannot be assured reliably. Without enough experience of the WLHPS is one of the reasons. The more important is the lack of the knowledge of how the weather, building characteristics, system style, heat source, etc. influencing the energy saving of the WLHPS. Therefore, it is worth doing further research on the application of the WLHPS in China by considering the actual situation.

2. Models for dynamic simulation

Considering the complexity of calculation, software for the design and simulation of building thermal environment, DeST [6], was used to calculate and analyze the dynamic air conditioning load of each room in a whole year.

2.1. Physical model

2.1.1. Various geographic locations

China is a country with a vast territory and with a manifold climate. The same WLHPS may result in difficult effects of energy saving when applied in the same building but different geographic locations because of the big differences of whether among these areas. So 12 cities in China were chosen as the representative for dynamic simulation in order to find the areas where the WLHPS could be applied suitably. The cities were ranked by latitude as Harbin, Urumqi, Beijing, Jinan, Lanzhou, Xi'an, Shanghai, Chengdu, Wuhan, Fuzhou, Kunming and Guangzhou.

2.1.2. Types of buildings

Four kinds of buildings were chosen as the calculation models (shown in Table 1). Type 1 was in the shape of long and narrow, which was similar to the conventional building in China. Types 2 and 3 were similar to the new type of commercial and residence buildings and type 4 was not commonly used, which was presented here just for comparison. They all faced north and south. The height of standard floor of the building was 3.60 m and, 2.85 m if considering the suspended ceiling.

It was found that there was less than 1% of difference in energy requirements for a 5-zone building compared to a 25-zone building, although theoretically speaking, more subareas the building were divided, more accurate the calculation results were [2]. So it could be deduced that there was not much influence on the actual results by simplifying the rooms in each floor in the building to several subareas. Therefore, 5 subareas in each floor in the building were adopted here in the model, among which 4 subareas were outer zone and 1 was inner zone (shown in Fig. 2). The commonly-used values for outer zone are 9–15 ft (2.74–4.57 m). The average value, 12 ft (3.6 m) was taken for the simulation here.

According to the actual situation of buildings in China, 490 mm thick outside wall was chosen for simulation in Harbin and Urumqi cities, 370 mm in Beijing, Jinan, Lanzhou and Xi'an, 240 mm in other cities, and 180 mm for inside wall in all cities. The outside wall was mainly composed from the air brick and the thermal resistance of 490, 370 and 240 mm thick wall are 0.627, 0.479 and 0.319 m^2 K/W, respectively. And all of the inside wall was mainly composed from the brick of 180 mm, whose thermal resistance is 0.802 m^2 K/W. The roof was made from the gas-concrete, whose thermal resistance is 0.607 m^2 K/W. Both of the floor and the ground floor were made from reinforced concrete, which their thermal resistance are 0.0975 and 0.026 m^2 K/W, respectively. As to the window, two layers of aluminum alloy glass window were chosen for simulation in Harbin

Table 1
Parameters of the buildings for simulation

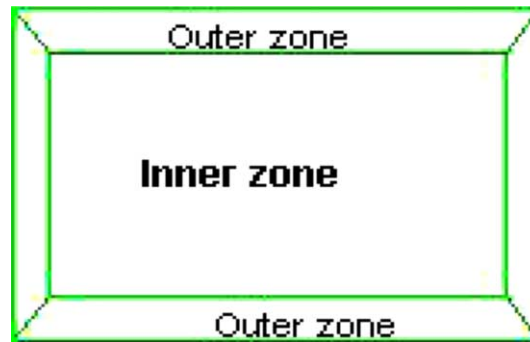| Number of building	Floors	Length (m)	Width (m)	Length-to-width ratio	Ratio of inner zone area to outer zone area
No. 1	4	54	10.5	5.14	0.37
No. 2	4	54	18	3	1.08
No. 3	4	54	27	2	1.47
No. 4	4	54	54	1	3.02

Fig. 2. Subareas plane of the building.

and Urumqi, and monolayer steel window in all the rest. No outside shading and inside curtain were considered in the simulation.

Room temperature was 20–22 °C in winter and 24–26 °C in summer and no special requirement for humidity.

Density of personnel in the building was taken as 0.25 m^{-2}, and, cooling load due to internal sources (such as equipment, people and lighting) was taken as 30 and 50 W/m^2, which represented the lower and medium interior load, respectively.

2.2. Mathematics model

Considering the capital cost being almost the same between the WLHPS and the conventional air conditioning system (CACS) [7,8], the operating cost was used to compare the energy consumption of the two systems and to decide the applicability of the WLHPS. And for simplification, it supposed that,

(1) the energy consumption of pumps and fans between the WLHPS and CACS was almost the same and was not considered in the simulation;
(2) the fresh air in the two systems were treated separately and were not considered in the comparison;
(3) electric energy was taken as index to compare the operating energy consumption for both systems.

As we know, CACS is the centralized air conditioning system with the centralized cooling/heat source and without the function of heat recovery. Therefore its operating cost can be calculated as follows,

$$E_1 = \frac{Q_C}{\varepsilon_{c1}\eta_d} + \frac{Q_H}{\eta_b} + \frac{Q_C(1 + 1/\varepsilon_{c1})}{\eta_{CT}\eta_d} \tag{1}$$

where E_1—operating energy consumption of CACS, kW; Q_C—cooling load of the building, kW; ε_{c1}—the average COP of the chiller in the centralized cooling source, here 4.0 is taken [9]; η_d—

total efficiency of electricity generating, $\eta_d = \eta_1 \times \eta_2$, where η_1 is efficiency of power electricity generating, usually ranges from 0.25 to 0.35 and η_2 is efficiency of electricity transport, $\eta_2 = 0.9$. So here 0.27 is taken for η_d; Q_H—heating load of the building, kW; η_b—efficiency of boiler, 0.75 is taken for coal-burning boiler [10] and 0.27 is taken for electric one (also in the type of electric energy, so efficiency of electricity generating is included); η_{CT}—coefficient of performance of cooling tower, defined as the ratio of the quantity of excluding heat of the cooling tower to its electricity consumption (including water pumps), here 100 is taken [2].

As to the WLHPS, the change of the quantity of heat in the circulation water caused by heat and cooling supply at the same time can be calculated by the following equation,

$$\Delta Q = Q_H(1 - 1/\varepsilon_h) - Q_C(1 + 1/\varepsilon_{c2}) \tag{2}$$

where ε_h—the average thermal coefficient of heat pump units, here 4.3 is taken [9]; ε_{c2}—the average COP of the heat pump units, here 3.5 is taken [9].

Thermal storage water tank can improve the effect of energy saving of the WLHPS. So when quantity of heat, ΔQ, is added in the water loop, the change of temperature of the system is,

$$\Delta t = \frac{3600\Delta Q}{\rho Vc} \tag{3}$$

where ρ—density of water in the loop, 1000 kg/m³ is taken here; V—volume of water in the WLHPS, including the water in the loop and the storage water tank, m³. Here the value of 10 l is taken for each square meter of the building; C—specific heat of water in the loop, 4.19 kJ/kg °C.

The temperature inside the water loop at a time is the difference of the temperature at the previous time plus the value of Δt.

Suppose t_{min}, t_{max} is the lower and upper limit of the range of temperature inside the water loop respectively (15 and 35 °C is taken respectively), then we can obtain,

(1) When $t > t_{max}$,

At this time, the quantity of heat sent out by the heat pump units is bigger than that the units got from the water loop and the temperature inside the loop is greater than the upper limit. So the cooling tower needs to be started. Therefore the operating energy consumption of the WLHPS is as follows,

$$E_2 = \frac{Q_C}{\varepsilon_{c2}\eta_d} + \frac{Q_H}{\varepsilon_h\eta_d} + \frac{1}{\eta_d\eta_{CT}}[Q_C(1 + 1/\varepsilon_{c2}) - Q_H(1 - 1/\varepsilon_h)] \tag{4}$$

where E_2—the operating energy consumption of the WLHPS (converting into electric energy), kW.

(2) When $t < t_{min}$,

At this time, the quantity of heat sent out by the heat pump units is less than that the units got from the water loop and the temperature inside the loop is smaller than the lower limit. So the boiler needs to be started. Therefore the operating energy consumption of the WLHPS is as follows,

$$E_2 = \frac{Q_C}{\varepsilon_{c2}\eta_d} + \frac{Q_H}{\varepsilon_h\eta_d} + \frac{1}{\eta_b}[Q_H(1 - 1/\varepsilon_h) - Q_C(1 + 1/\varepsilon_{c2})] \tag{5}$$

(3) When $t_{min} < t < t_{max}$,

At this time, the quantity of heat sent out by the heat pump units is almost the same as that the units got from the water loop. Neither the cooling tower nor the boiler needs to be started. Therefore the operating energy consumption of the WLHPS is as follows,

$$E_2 = \frac{Q_C}{\varepsilon_{c2}\eta_d} + \frac{Q_H}{\varepsilon_h\eta_d} \tag{6}$$

In order to make the comparisons of energy consumption between the CACS and WLHPS clearly, the rate of energy saving of the WLHPS, E_{sp}, is introduced here. Its definition is as follows,

$$E_{sp} = \frac{E_1 - E_2}{E_1} \times 100\% \tag{7}$$

where E_{sp}—the rate of energy saving of the WLHPS.

If $E_{sp} > 0$, then applying the WLHPS has more effect of energy saving than applying the CACS, the bigger the value is, the more energy is saved, and vice versa.

3. Applicability analysis

Based on the mathematical model above, the whole year energy consumption and its comparisons between the CACS and WLHPS in different buildings and different geographic locations could be obtained.

3.1. When electric boiler is used

Fig. 3 shows the comparisons of energy consumption of building 1–4 between the CACS and WLHPS when inner load is at 50 W/m² in different cities in China. The rate of energy saving of the WLHPS of building 1–4 when inner load is at 50 W/m² in different cities in China can be calculated based on formula (7). The results are shown in Fig. 4, respectively.

It can be seen from Figs. 3 and 4 that the maximum effect of energy saving ($E_{sp} = 19.10\%$) is occurred in building 3 in Harbin when the inner load is of 50 W/m² and better effect mainly in the northern part of China. This is because the superiority of the WLHPS lies at its heat recovery when cooling and heating load are demanded at the same time and the energy consumption of cooling tower and boiler can be decreased. So the potential effect of energy saving of the WLHPS should reach maximum in winter. And it is a little colder in winter in northern part of China and the time of heat supply is longer, especially when the inner zone area is larger, the quantity of heat transfer between the building and outside air is smaller, and cooling supply is needed in the inner zone even in winter, therefore there is much waste heat can be transferred to the outer zone for its heat supply and thus energy is saved. But as the area of inner zone increases, the cooling load in summer will rise greatly, which makes it possible that the increase of energy consumption for cooling supply in summer is larger than the decrease of that for heat supply in winter and, the rate of energy saving of the WLHPS may reduce and even becomes negative.
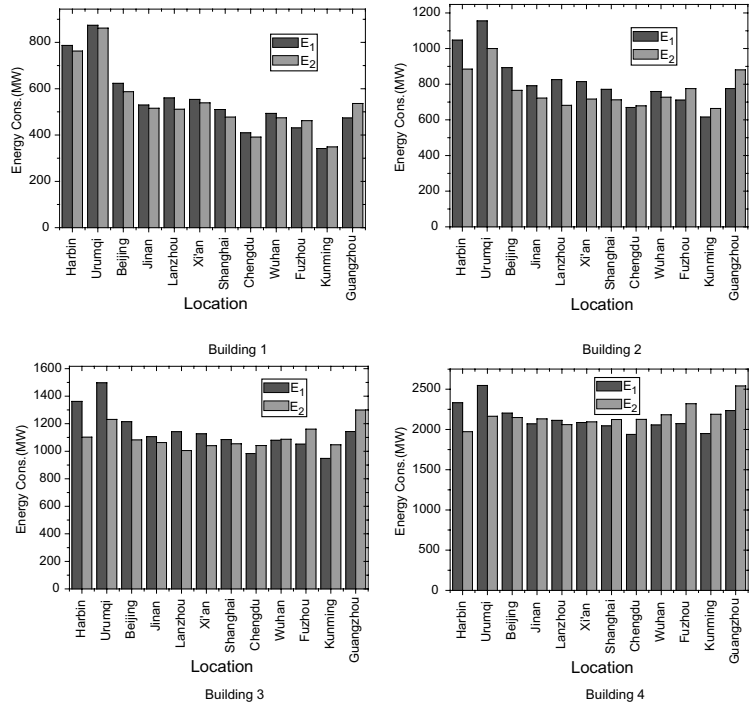
Fig. 3. Comparisons of energy consumption of building 1–4 between CACS and WLHPS when inner load at 50 W/m^2. E_1 is the operating energy consumption of CACS and E_2 is for the WLHPS.
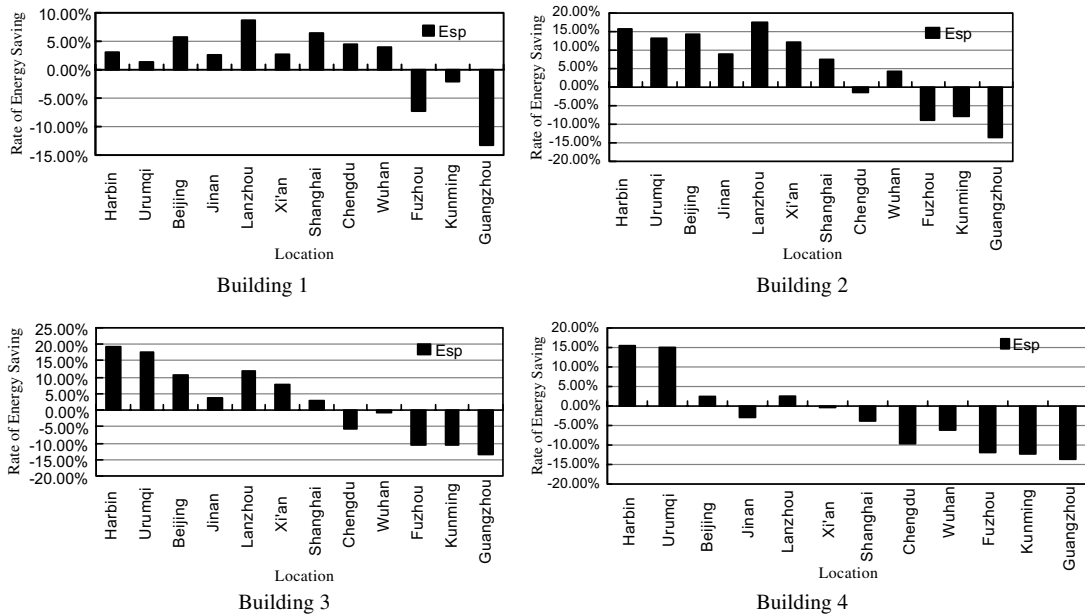

Fig. 4. Rates of energy saving of building 1–4 when WLHPS applied at inner load of 50 W/m^2.

It can also be seen from Figs. 3 and 4 that the worst effect of energy saving is occurred in Guangzhou and it is true for all of the buildings. The value of the rate of energy saving of the WLHPS is negative, which means the WLHPS consumes more energy than the CACS does. This is because the weather in Guangzhou is warmer in winter and there is no requirement for heat supply, and in summer the time of cooling supply is longer, the COP of heat pump unit is smaller than that of centralized refrigeration chiller, therefore applying the WLHPS does not have any effect of energy saving, instead.

The similar results can be obtained when the inner load is of 30 W/m^2. At this case, the maximum rate of energy saving can reach to 19.29% when it is applied in building 3 in Lanzhou city. Fig. 5 shows the comparisons of energy consumption between the two systems and the rates of energy saving of the WLHPS applied in building 2.

From the results above it can be seen that the WLHPS has an obvious effect of energy saving when electric boiler is used. The main districts where the rate of energy saving of the WLHPS is positive include the areas along the Coast of Yangtze River and its northern parts. The maximum of the rate of energy saving of the WLHPS usually occurs in the areas where it is a little colder. And it does not have obvious effect of energy saving, and even consumes more energy, to apply the WLHPS in the southern parts from Yangtze River, especially in the areas of south China.

Considering the other advantages of the WLHPS, such as being charged individually easily, the districts can be thought suitable to apply the WLHPS when there is no big difference of energy consumption between it and the CACS, say −5% or −10%, which is shown in Fig. 6, north from the line (where the red dashed line based on −5%).
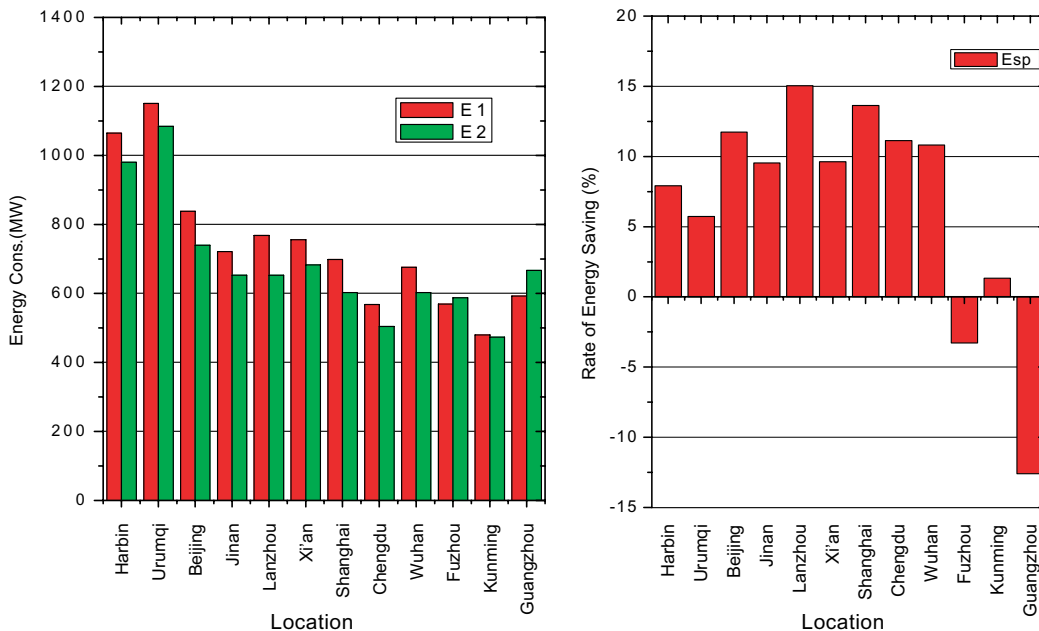

Fig. 5. Comparisons of energy consumption and rates of energy saving of building 2 at inner load of 30 W/m^2.

Fig. 6. Suitable applied areas of WLHPS when electric boiler used in China. (For the colour version of this figure, the reader is referred to the web version of this article.)

3.2. When coal-burning boiler is used

There are many kinds of heat sources, such as coal/oil/gas burning boiler, solar energy collector, centralized heat supply, wasted heat and so on, that can take into account to be used for the WLHPS besides the electric boiler. Different types of heat sources will cause different characteristics of energy saving. Coal-burning boilers are still used for heat supply in some districts in China because of the shortage of electricity and the much lower price of coal.

It was obtained in Ref. [9] that applying the WLHPS did not have any effect of energy saving no mater how much the wasted heat there was in the building when coal-burning boiler was used as the heat source. Results in the paper also demonstrate it. Fig. 7 is one of those.
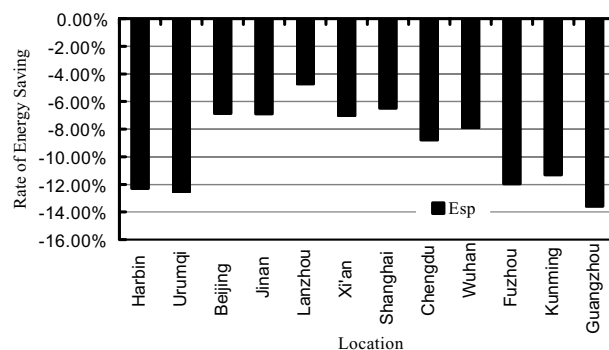

Fig. 7. Rates of energy saving of building 3 when WLHPS applied at inner load of 30 W/m^2 and coal-burning boiler used.

Fig. 8. Suitable applied areas of WLHPS when coal-burning boiler used in China.

But the results also show that, when coal-burning boiler is used as the heat source, the larger inner load and the bigger ratio of inner zone floor area to outer zone floor area can reduce the difference of the operating energy consumption between the WLHPS and CACS, which is still beneficial to the northern parts. The figures are omitted because of the limitation of the space.

If bounding based on the rate of energy saving bigger than −10%, the area is shown between the two lines in Fig. 8. In this range, there is no big difference of the operating energy consumption between the WLHPS and CACS, so it is possible to apply the WLHPS considering its special advantages. Whether the WLHPS can be applied or not depends on the technical and economic comparisons in an actual project.

3.3. Characteristics of energy saving of the WLHPS

Characteristics of energy saving of the WLHPS are influenced by both the ratio of inner zone area to outer zone area and the inner load. Just as shown in the results above, as the increase of the inner load, the maximum value of the rate of energy saving moves northward. The larger inner load is beneficial to the northern parts, but energy will be consumed more if the inner load reaches to a certain value and continues rising. And the smaller inner load is beneficial to the southern areas.

As to the types of buildings, the concept of heating–degree–days can be used to analyze its effect. Heating–degree–days is a quantitative index demonstrated to reflect demand for energy to heat or cool houses and businesses. Taking an electric boiler used as a heat source as an example, the relations between the rate of energy saving of the WLHPS and heating–degree–days are shown in Fig. 9. It is also shown in the figure that the increase of the ratio of inner zone area to outer zone area will also make the maximum value of the rate of energy saving have the tendency to move to the bigger value of the heating–degree–days, or move northward. Just similar to the effect of inner load inside a building, the larger ratio of inner zone area to outer zone area is beneficial to
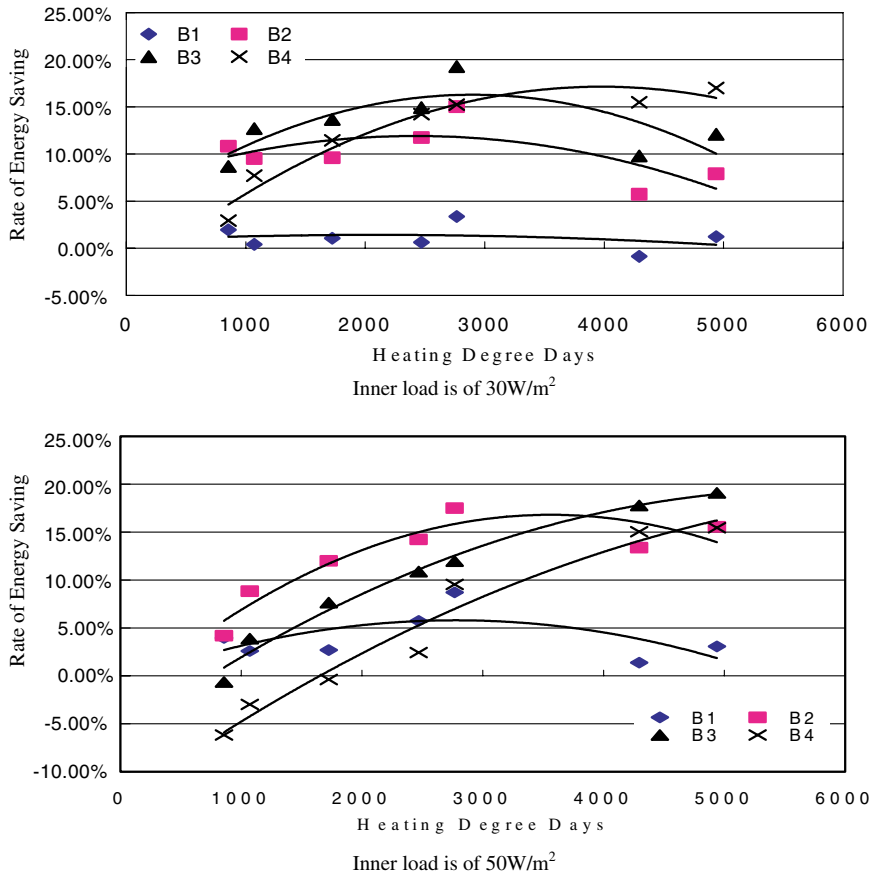
Fig. 9. Relations between rate of energy saving of WLHPS and heating–degree–days at different inner load.

the northern parts, because there will be greater amount of wasted heat that can be recovered. The mezzo ratio of area is beneficial to the regions along the Coast of Yangtze River and the smaller ratio of area is beneficial to the southern areas since the cooling load can be much less.

It can be seen from Fig. 9 that the rate of energy saving of building 1 is less affected by heating–degree–days and it fluctuates near the value of 0. This is because the enclosures of buildings vary with their geographic locations and the cooling load in the summer in the north is less. The calculation results show that most of the whole year loads in building 1 are resulted from the outer zone and there are few chances to realize the heat balance. So the loads are greatly affected by the weather and there is a distinct difference of load among the cities. With the increase of the area of inner zone, the load resulted from the inner zone becomes the main part gradually. The whole year loads of buildings in different areas, especially the whole year loads of the WLHPS, are much less influenced by weather with almost equivalent magnitude.

It can be deduced that the mezzo inner load and the mezzo ratio of inner zone area to outer zone area are most suitable to the application of the WLHPS.

The concept of the ratio of cooling load to heating load of a building can also be used to analyze the applicability of the WLHPS. To express clearly the relation of the rate of energy
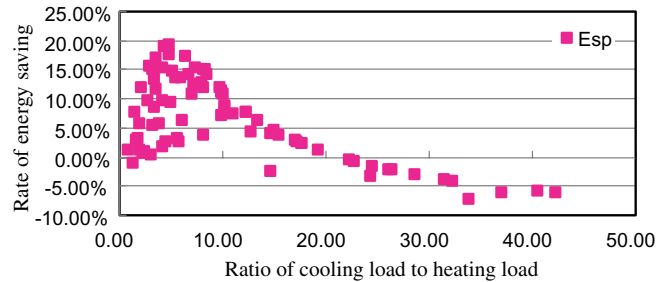
Fig. 10. Relations between rate of energy saving of WLHPS and ratio of cooling load to heating load E_{sp} is the rate of energy saving of the WLPHS.

saving and the ratio of cooling load to heating load, some extreme values of the individual ratios were omitted when constructing because the range of the ratio of cooling load to heating load in the calculation was much great, from 0.817 in Harbin to 7387.5 in Guangzhou, for instance. The relation is shown in Fig. 10.

It can be seen from Fig. 10 that there is an obvious correlation between the rate of energy saving and the ratio of cooling load to heating load. When the ratio of cooling load to heating load equals 0, all the energy is consumed for heat supply and there is no difference between the WLHPS and CACS when electric boiler is used, so the rate of energy saving equals 0 too. As the increase of the ratio of cooling load to heating load, the cooling load that can balance the heating load goes up, so the rate of energy saving rises too. When the balance point of heat recovery is reached to, the continued increase of the ratio of cooling load to heating load will not make the heat recovery better. On the contrary, it will reduce the rate of energy saving and even make it negative because the COP of the small heat pump unit is less than that of CACS. In the calculation cases in the paper, the most suitable ratio of cooling load to heating load for the WLHPS is about 4.8. And considering the other advantages of it, the WLHPS can be applied in the buildings where the ratio of cooling load to heating load is not more than 42, and the rate of energy saving is greater than −5% at this time.

4. Conclusions

1. The WLHPS has an obvious effect of energy saving when electric boiler is used. It can be applied in the most districts in China particularly in the areas along the Coast of Yangtze River and its northern parts. And it does not have obvious effect, and even consumes more energy, to apply the WLHPS in the southern parts from Yangtze River, especially in the areas of south China.
2. Characteristics of energy saving of the WLHPS are influenced by both the ratio of inner zone area to outer zone area and the inner load. The mezzo inner load and the mezzo ratio of inner zone area to outer zone area are most suitable to the application of the WLHPS.
3. In the calculation cases in the paper, the maximum rate of energy saving can reach to 19.29%, and the most suitable ratio of cooling load to heating load for the WLHPS is about 4.8.

Considering the other advantages of it, the WLHPS can be applied in the buildings where the ratio of cooling load to heating load is not more than 42.

4. Applying the WLHPS has no effect of energy saving compared with CACS when coal-burning boiler is used as the heat source under the current policy of energy in China now. But the larger inner load and the bigger ratio of inner zone area to outer zone area can reduce the difference of the operating energy consumption between the WLHPS and CACS in the northern parts. So it is still possible to apply the WLHPS there considering its special advantages. Whether the WLHPS can be applied or not should depend on the technical and economic comparisons in an actual project.

Acknowledgements

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