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A new inverter heat pump operated all year round with domestic hot water

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Abstract

This paper presents a new scheme of an inverter air cooling heat pump system with domestic hot water. A water reheater is placed between the compressor outlet and the four way valve inlet to utilize the sensible heat of the superheated gas exhausted from the compressor, and a water preheater is placed between the condenser and the throttling device to use the sensible heat of the subcooled liquid flowing out of the condenser. With these two parts of heat, the domestic hot water can be heated to a temperature high enough for domestic use. In order to maintain the system efficiency in the period of part load, an inverter compressor is adopted as the substitute for the constant speed one used in the conventional heat pump system. A hot water storage tank with a circulation pump is placed in the system to reduce the peak load of the system. Compared with the traditional system, this new design is able to reduce energy consumption by 31.1% and decrease thermal pollution to the environment.

Keywords: Domestic hot water; Heat pump; Heat recovery; Variable speed compressor

1. Introduction

Heat pump air conditioners are widely used in residential buildings nowadays, especially in China. The application of residential air conditioners has a large increase in the last decade. There were more than 20 million new air conditioners put into use in the year 2001. In a conventional residential heat pump air conditioner, the waste condensation heat is exhausted to the outdoor surroundings vainly in the summer, which not only engenders energy waste but also yields thermal pollution to the outdoor environment. The energy consumption and the thermal pollution are

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huge, not only in China but also in the world. To a modern urban family, domestic hot water is necessary for daily life and is usually provided by a domestic water heater making use of electricity or gas, which is known for its great energy expenditure. As we know, the condensing temperature of a heat pump is about 50 °C, and the temperature of domestic hot water is about 45 °C or so. So, proper recovery of waste condensing heat to produce domestic hot water is a kind of efficient means of comprehensive energy utilization [1]. Therefore, the development of a heat pump system with domestic hot water is of great potential to save energy and decrease thermal pollution.

Current studies are mostly focusing on the following two schemes: (1) to use a water cooled condenser to replace the air cooled condenser [2,3] or (2) to add a desuperheater at the outlet pipe of the constant speed compressor [4–6]. A system with scheme (1) can normally operate in summer when the room needs cooling, but in winter, the room needs to be heated. Thus, the water cooled heat exchanger acts as an evaporator, and the water in it is cooled, even to freezing, and can not provide domestic hot water. Therefore, some other separate equipment is needed to heat the room and to supply domestic hot water in winter, which means there are two or more different systems installed in the room. The whole system becomes more complex, and both the occupied space and the equipment initial cost increase significantly. A system with scheme (2) can operate in winter, but the compressor with constant speed may fail to supply enough heating and domestic hot water at the same time unless a larger system and components are selected, which is not efficient and economical.

This paper presents a new scheme of residential heat pump air conditioner with condensation heat recovery to produce domestic hot water. Such a system is able to operate all year round and produce domestic hot water at the same time. The feasibility and operation performance of the system are studied in detail, and the economic analysis of the system is given.

2. Configuration and principle of the new system

Fig. 1 shows a new scheme of inverter air cooling heat pump system with domestic hot water. In order to clearly show the similarity and difference between the heat pump with domestic hot water and the traditional heat pump, the simplified schematic of the new heat pump is shown in Fig. 2. Compared with the traditional heat pump with only one condenser and one evaporator, two additional water-refrigerant heat exchangers are installed. One of them, the domestic hot water reheater, is placed between the compressor outlet and the four way valve inlet, and the other, the domestic hot water preheater, is placed between the condenser and the throttling device. By this way, the sensible heat of the superheated gas exhausted from the compressor and the sensible heat of the subcooled liquid flowing out of the condenser are both recovered, and the domestic water can be heated to a temperature high enough for use. Apart from utilization of the waste heat, such a scheme also helps to improve the system performance by further subcooling the liquid refrigerant before it enters the throttling device. If domestic hot water is not in use, there is little heat exchanged in the preheater and reheater, and the preheater and reheater act only as connecting pipes. The resulting system has only one condenser and evaporator, which is the same as the traditional heat pump system. There is some refrigerant in the preheater and the reheater whether they are in use or not, which should be considered to determine the total refrigerant charge in the system, and there is a refrigerant receiver tank to balance the change in refrigerant charge. Thus, if

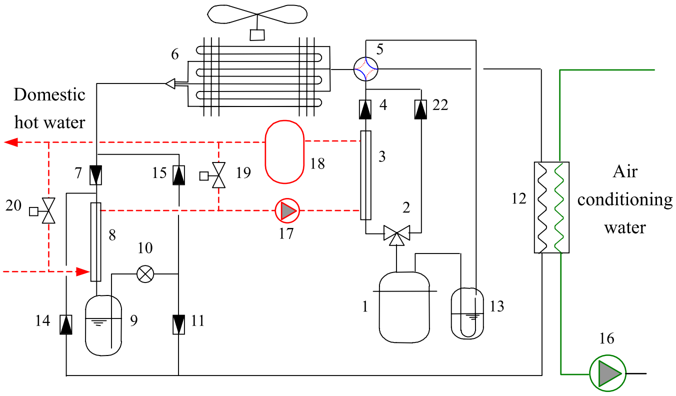

Fig. 1. Configuration of the system: (1) compressor, (2) three way valve, (3) reheater, (4, 7, 11, 14, 15, 22) check valve, (5) four way valve, (6) air refrigerant heat exchanger, (8) preheater, (9) receiver tank, (10) throttling devices, (12) water-refrigerant heat exchanger, (13) gas–liquid separator, (16) air conditioning water pump, (17) domestic water pump, (18) domestic water tank, (19, 20) electromagnetic valve.

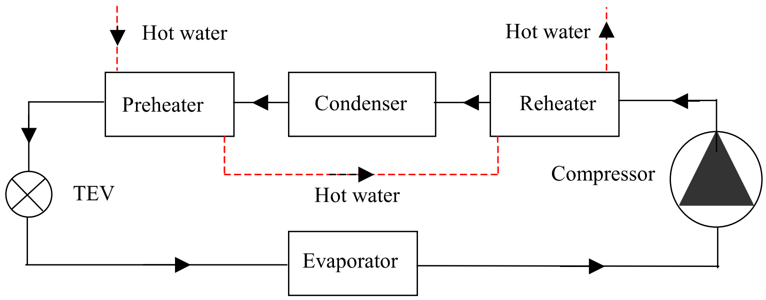

Fig. 2. Schematic diagram of the heat pump system.

the hot water is not in use, the performance of the new system is nearly the same as that of the traditional heat pump.

The operating condition of the heat pump system varies greatly during one year, which has a significant influence on the all year round performance of the entire system. In order to solve this problem, the heat pump system studied in this paper is equipped with an inverter compressor. This compressor is able to regulate the system cooling/heating capacity continuously and effectively to fulfill the peak load by operating at a higher speed, which greatly improves the annual performance factor (APF) [7–9].

To reduce the peak load of the system, a hot water storage tank with a circulation pump is placed in the system. When the domestic hot water is not in use, the water in the tank is pumped to the reheater to be heated and then stored, which solves the problem of insufficient heat supply in the winter condition.

Furthermore, a three way valve is mounted between the compressor and the four way valve of the heat pump. This valve has two operating modes: one is to allow the refrigerant flow from the compressor into the four way valve directly and the other is to make the refrigerant from the compressor flow into the water reheater before it flows into the four way valve. One of the most important functions of this valve is to prevent the liquid refrigerant from flowing into the four way valve. If the refrigerant at the outlet of the water reheater is cooled to the saturated state, the valve will make the refrigerant flow from the compressor into the four way valve directly. If the temperature is too high, some dirt will be separated from the water and stick on the inside surface of the heat exchanger, which will plug the water circuit in the heat exchanger. This valve is able to keep the temperature in a safe range by controlling the flow direction of the refrigerant.

Domestic hot water is needed all year round, although the house mainly needs cooling in the summer while it needs heating in the winter. During the transitional seasons, the house may need only domestic hot water. This system can operate in five modes:

1. *Cooling only mode*. In this mode, the reheater, preheater and domestic water pump are not in use, and the air heat exchanger acts as a condenser while the water heat exchanger acts as an evaporator as shown in Fig. 3. The vapor refrigerant discharged from the compressor (1) flows into the air heat exchanger (6) directly through the three way valve (2), the check valve (22) and the four way valve (5) and is condensed there. The liquefied refrigerant flows through check valve (7) and the preheater (8) with little heat exchanged, then to the receiver tank (9) and is depressurized by the throttling device (10). The depressurized refrigerant flows through the check valve (11) to the water heat exchanger (12). The refrigerant is evaporated and then returns to the compressor (1) through the four way valve (5) and the gas–liquid separator (13).

2. *Cooling with hot water*. In this mode, the reheater, preheater and air heat exchanger act as condensers, while the water heat exchanger acts as an evaporator. The refrigerant flow path is the same as that in the cooling only mode, but the three way valve makes the refrigerant flow through the reheater (3) to heat the domestic water and then enter the four way vavle (5), which is also shown in Fig. 3. The domestic hot water is pumped through the preheater, reheater and storage tank one by one.

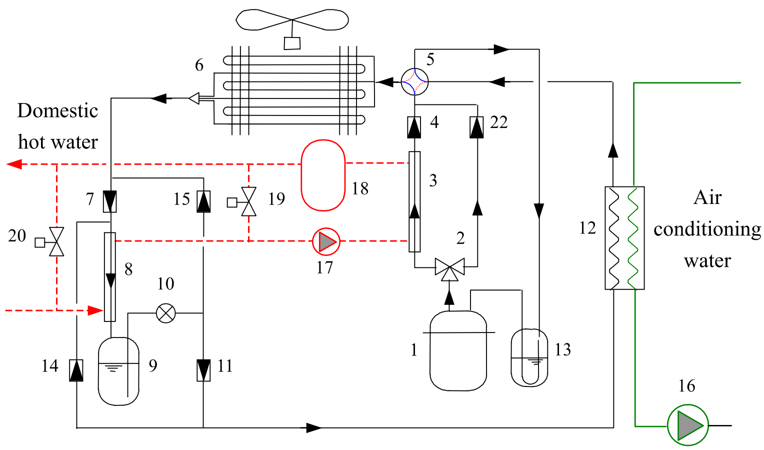

Fig. 3. Refrigerant flow paths in cooling only and cooling with hot water mode.

3. *Heating only mode.* In this mode, the reheater, preheater and domestic water pump are also not in use, and the air heat exchanger acts as an evaporator, while the water heat exchanger acts as a condenser as shown in Fig. 4. The vapor refrigerant discharged from the compressor (1) flows into the water heat exchanger (6) directly through the three way valve (2), the check valve (22) and the four way valve (5) and is condensed there. The liquefied refrigerant flows through the check valve (7) and the preheater (8) with little heat exchanged, then to the receiver tank (9) and is depressurized by the throttling device (10). The depressurized refrigerant flows through the check valve (11) to the water heat exchanger (12). The refrigerant is evaporated and then returns to the compressor (1) through the four way valve (5) and the gas–liquid separator (13).

4. *Heating with hot water*. In this mode, the reheater, preheater and water heat exchanger act as condensers while the air heat exchanger acts as an evaporator. The refrigerant flow path is the same as that in the heating only mode, but the three way valve (2) makes the refrigerant flow through the reheater (3) to heat the domestic water and then enter the four way valve (5), which is also shown in Fig. 4. The domestic hot water is pumped through the preheater, reheater and storage tank one by one.

5. *Domestic hot water only*. In this mode, the water heat exchanger is not in use, and the reheater and preheater act as condensers, while the air heat exchanger acts as an evaporator. The refrigerant flow path is the same as that in the heating with hot water mode, but the refrigerant flows through the water heat exchanger with little heat exchanged since there is no water flowing in it, which is also shown in Fig. 4. The domestic hot water is pumped through the preheater, reheater and storage tank one by one.

These five modes make it possible for the system to provide heating, cooling and domestic hot water all year round. When the system is operating in the cooling only mode or the heating only mode, it is the same as a traditional inverter heat pump system.

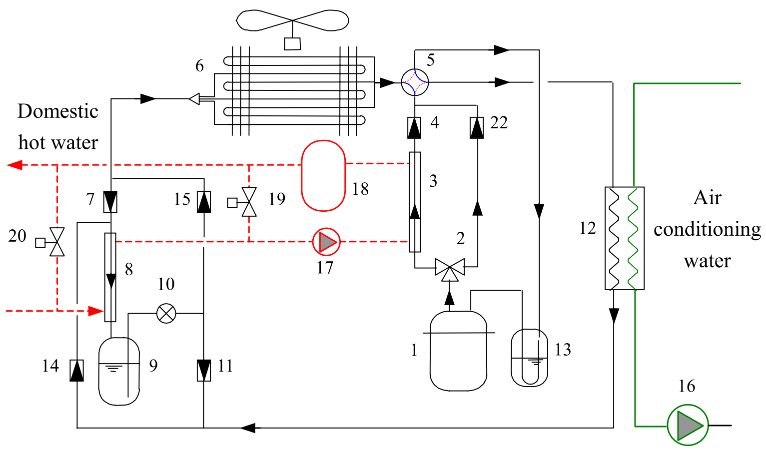

Fig. 4. Refrigerant flow paths in heating only, heating with hot water and hot water only mode.

3. System performance analysis

3.1. Performance improvement on thermodynamic cycle

The thermodynamic cycle of this system is shown in Fig. 5. The thermodynamic performance is improved in two ways. One way is from the reheater, which lowers the compressor discharge temperature and elevates the domestic water temperature simultaneously. Because the compressor discharge temperature is very high, the domestic water can be heated to the required temperature without raising the condensing temperature. The other way is from the preheater, which increases the subcooling degree. Therefore, both Δh_1 and Δh_5 are increased.

When the hot water is not in use, because there is little heat exchanged in the reheater and preheater, there is only one condenser and one evaporator, which is the same as the traditional heat pump system.

3.2. Energy efficiency ratio

The energy efficiency ratio (EER) is an important parameter to evaluate system performance. The EER of this kind of heat pump system can be expressed as

$$\mathrm{EER} = \frac{\sum Q}{\sum W} = \frac{Q_{\mathrm{water}} + Q_{\mathrm{room}}}{\sum W} \tag{1}$$

In mode (1), the hot water is not in use, so only the evaporating heat is used for room cooling:

$$\mathrm{EER} = \mathrm{EER}_1 = \frac{\Delta h_5}{W} \tag{2}$$

In mode (2), in addition to the evaporating heat being used for room cooling, a part of the condensing heat is recovered to heat the domestic hot water:

$$\mathrm{EER} = \mathrm{EER}_2 = \frac{\Delta h_1 + \Delta h_3 + \Delta h_5}{W} \tag{3}$$

In modes (3)–(5), all the condensing heat is used for rooming heating and/or domestic hot water:

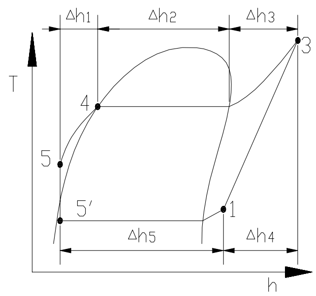

Fig. 5. Cycle in *T*–*h* diagram.

$$\mathrm{EER} = \mathrm{EER}_3 = \frac{\Delta h_1 + \Delta h_2 + \Delta h_3}{W} \tag{4}$$

In modes (1) and (3), the hot water is not in use. Because there is little heat exchanged in the reheater and preheater, there is only one condenser and one evaporator in the heat pump system. All the evaporating heat is used for room cooling in mode (1), and all the condensing heat is used for room heating in mode (3), which is the same as the traditional heat pump system. So EER_1 and EER_3 are the same as that of traditional heat pump systems, but the advantages of this system are that the condensing heat becomes useful when the system operates in the cooling with hot water mode and the improvement of the thermodynamic cycle by the preheater and reheater.

3.3. Performance analysis by simulation

The performance of the system is calculated by an appropriate simulation model of an inverter air conditioning system [10,11]. The models of the variable speed compressor and expansion valve are based on experimental data in different conditions. The heat exchangers are taken as a series of finned tubes and calculated by the distributed parameter method. The difference between the model of the new heat pump system and that of the traditional system is that there are three condensers connected in series, which are easily solved by the distributed parameter method. The system model is solved with an iterative method by the three control equations of mass conservation, energy conservation and momentum conservation. With the given outdoor air temperature, indoor air conditioning load and structure parameters of the heat pump system, the energy consumption and energy efficiency ratio (EER) can be calculated. The performance characteristics of this system can be defined by simulation, and the all year round operation performance can be calculated on the basis of these characteristics.

Based on the above definitions of the EERs in the different modes, the operation performances of each mode have been calculated by computer. The working conditions for the calculations are shown in Table 1.

3.4. Performance in summer

Fig. 6 shows the calculation results of EER in the cooling with domestic hot water mode and the cooling only mode. It shows that when the system operates in the cooling with domestic hot

Table 1
Working conditions for calculation

Items	Modes 1 and 2	Modes 3 and 4	Mode 5
Outdoor dry bulb temperature (°C)	35	7	21
Outdoor wet bulb temperature (°C)	24	6	14
Inlet air conditioning water temperature (°C)	12	40	–
Outlet air conditioning water temperature (°C)	7	45	–
Inlet hot water temperature (°C)	15	15	15
Outlet hot water temperature (°C)	45	45	45

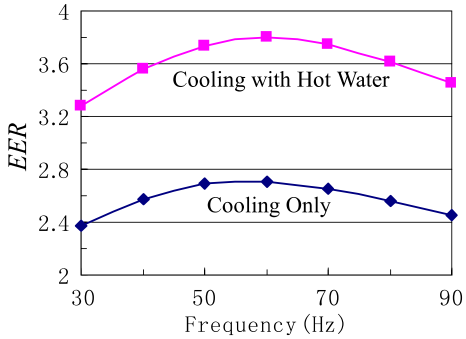

Fig. 6. EER in cooling modes.

water mode (2), the EER is about 90% higher than that in the cooling only mode (1). This is mainly because of the preheater and reheater. The reheater absorbs part of the heat of the gaseous refrigerant at the outlet of the compressor, and then the condensation temperature is decreased. So the EER of the system is higher than that of the conventional system. The preheater increases the subcooling degree and increases the useful enthalpy difference, and the refrigerating capacity is higher than before. When the heat pump operates in the cooling only mode (1), it is a traditional heat pump. Therefore, the condensation heat recovered to make domestic hot water is the main advantage compared with the traditional heat pump when the room needs to be cooled.

3.5. Performance in winter

From Fig. 7, we can find that the EER is about 10% higher in the heating with hot water mode (4) than in the heating only mode (3). This is also due to the preheater and reheater. The domestic hot water increases the subcooling degree and increases, the useful enthalpy difference. Thus, the cycle efficiency is improved, and more heat comes to the application with the same energy input. This is the superiority of this system relative to the traditional heat pump when the room needs to be heated. Although the room heating load and the hot water load make the system load increase, it can be satisfied by the inverter compressor operating at a higher frequency.

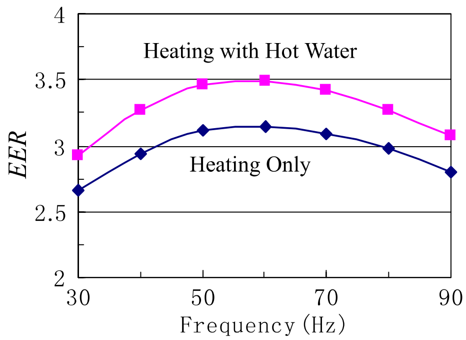

Fig. 7. EER in heating modes.

3.6. Performance in transitional seasons

In the spring and autumn, the heat pump system may not be used to cool or heat the room space. It can be used to provide domestic hot water separately. In this case, the reheater and preheater are used as condensers, and the outdoor heat exchanger is used as an evaporator. Because the high outdoor temperature leads to decreasing the difference between the condensing temperature and the evaporating temperature, the EER of this system can reach a high value of about 4.0, as shown in Fig. 8. Therefore, in transitional seasons, the input energy to produce domestic hot water is very little. Compared with the electric water heater, whose EER is no more than 1.0, this scheme can save more energy.

3.7. Performance in different outdoor temperature

The EER is a function of the frequency and outdoor air temperature in each mode. Especially at a constant speed, there is a linear relationship between EER and the outdoor air temperature [12], as shown in Eq. (5):

$$\mathrm{EER}(T_o) = \mathrm{EER}(T_{o,0}) + k \cdot (T_o - T_{o,0}) \tag{5}$$

where

$$k = \frac{\mathrm{EER}(T_{o,1}) - \mathrm{EER}(T_{o,0})}{T_{o,1} - T_{o,0}} \tag{6}$$

The values of k in different frequency are shown in Fig. 9, from which a new function to calculate k is gained and expressed as Eq. (7).

$$k = 0.0006f - 0.1242 \tag{7}$$

The frequency of the compressor is determined by the load of air conditioning and domestic hot water, which will be discussed in the next part.

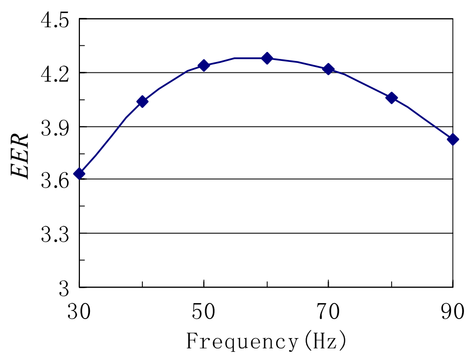

Fig. 8. EER in hot water only mode.

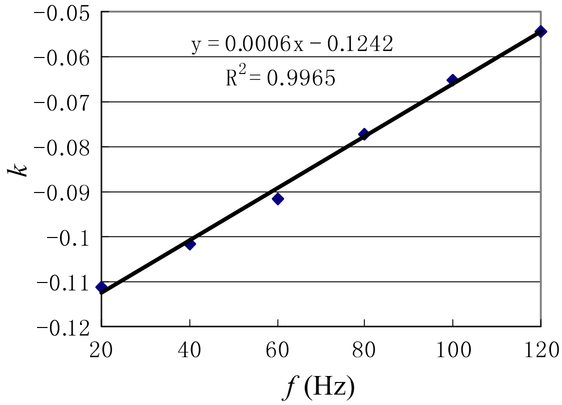

Fig. 9. k in different frequency.

4. Economic comparison

As discussed above, such a system is most suitable for residential buildings in which cooling and domestic hot water is needed all year round, but the climate varies in different areas in China. For example, cooling is needed in most of the year and little heating is needed in the south of China, but in the middle and north of China, cooling is needed in the summer and heating in the winter. From the south to the north, the heating load becomes higher and higher. Beijing is the north end where an air source heat pump can be used all year round. If an area is north of Beijing, the air temperature in winter is too low to operate the heat pump, and its capacity is not enough for heating in the area. So, a residential building in Beijing is selected to evaluate the energy efficiency of this new scheme of heat pump. If this kind of heat pump is used in the south of China, it will be more economical than when used in Beijing.

A feasible load model is the premise for system performance analysis in its all year round operation. This load model should include two parts, the room air conditioning load and the required hot water quantity. Based on the description of the house envelope and the living mode of a typical family, the room load model is constructed.

4.1. Room air conditioning load model

Fig. 10 shows the house plan of a typical Beijing family. It is a two storied villa building, and the thicknesses of the outside brick wall and inside wall are 24 and 18 cm, respectively.

This family consists of six people: two old people, two middle aged people, one child and a nursery maid. The two middle aged people and the child usually leave home at 7:00 and go back home at 18:00. The other three people stay at home all day long. Normally, they go to bed at about 22:00 and then get up at 6:00 every day.

Designer's Simulation Toolkit (DeST), developed by the Department of Building Science, Tsinghua University, is a simulation toolkit for HVAC designers. It can simulate the thermal environment of a building [13–15]. In this study, DeST is used to calculate the air conditioning load of the house with the living mode described above. In the calculation, the room temperature

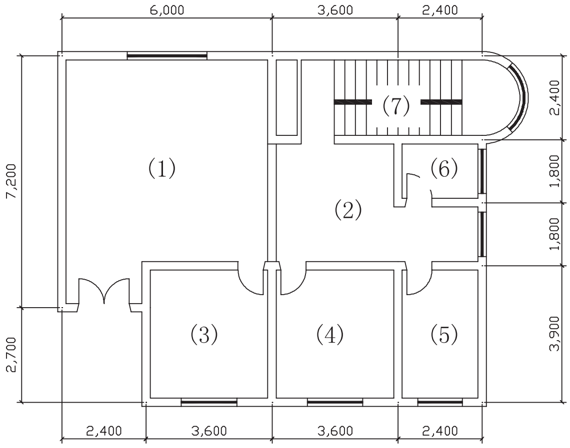

Fig. 10. Plane figure of the house: (1) sitting room, (2) dining room, (3) bedroom 1, (4) bedroom 2, (5) kitchen, (6) washing room.

is set at 24–26 °C in summer from May 16 to September 15 and 18–20 °C in winter from November 1 to March 31. The time step is one hour during the calculations, and the hour to hour air conditioning load is calculated. The results of the calculations for this house are shown in Figs. 11 and 12.

4.2. Required hot water quantity

To a modern urban family, domestic hot water is necessary for daily bathing and washing. Therefore, determining the required hot water quantity model is the key to determining the required hot water quantity during one bath time of the family. According to previous investigations [16,17], 120 l of 45 °C hot water is enough for one bath. In the summer and transient

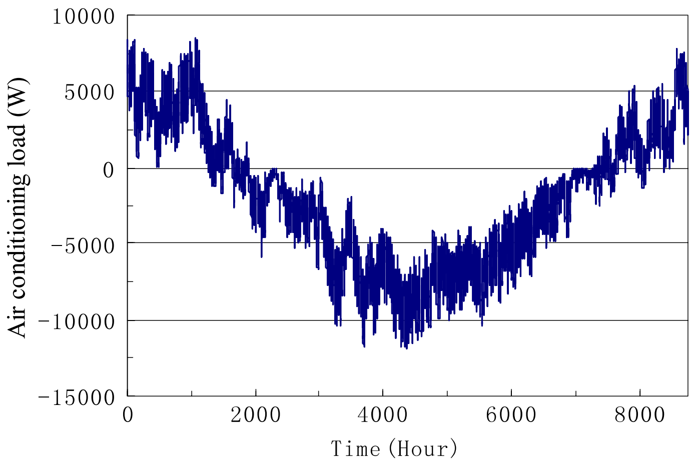

Fig. 11. Air conditioning load calculation result.

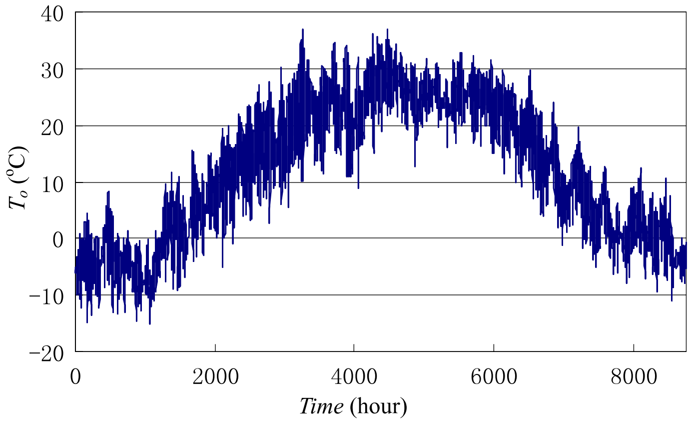

Fig. 12. Outdoor air temperature.

seasons, each person takes one bath every day, while in winter, each takes one bath every two days. So, in winter, the required hot water quantity of the whole family for baths is 360 l per day, and in other times, 720 l per day. Considering the hot water quantity for washing, the required quantity can be up to 410 l per day in winter and 770 l per day in other times.

The inlet temperature of tap water is usually 15 °C, so in order to supply domestic hot water of 45 °C, the heat needed can be calculated as follows.

In winter:

$$Q = 410 \times 4180 \times (45 - 15) = 4.14 \times 10^7 \text{ (J)} \tag{8}$$

while in other times, the heat is:

$$Q = 770 \times 4180 \times (45 - 15) = 9.66 \times 10^7 \text{ (J)}. \tag{9}$$

4.3. Calculation results and comparison

The annual performance factor (APF) is used to evaluate the energy efficiency of the different systems. As shown in Eq. (10), the APF of the system is defined as the ratio of the total energy gain to the total energy consumption,

$$\text{APF} = \frac{\sum Q}{\sum P} = \frac{\sum_{i=1}^{8760} Q(i)}{\sum_{i=1}^{8760} P_{\text{in}}(i)} \tag{10}$$

Based on the house load and the system performance discussed above, the energy consumption of the all year round operation can be calculated according to Eq. (10). The annual performance factor of this system is compared with that of a traditional heat pump plus electric water heater. The results are shown in Table 2.

To make the domestic hot water, the electric water heater operates all year round with an efficiency no more than 1.0. The total load of domestic hot water is 2.833×10^{10} J in a year, so the electrical energy consumed is at least 2.833×10^{10} J by the electric water heater. The heat pump

Table 2
Calculation results of the two systems

	Inverter air cooling heat pump system with domestic hot water	Inverter air cooling heat pump system plus electric water heater
Room air conditioning load (J)	1.293×10^{11}	1.293×10^{11}
Domestic hot water load (J)	2.833×10^{10}	2.833×10^{10}
Auxiliary electricity consumption for hot water (J)	2.173×10^{9} (in spring and autumn)	2.833×10^{10} (in a year)
Electricity consumption of heat pump system (J)	4.707×10^{10}	4.310×10^{10}
Total electricity consumption (J)	4.924×10^{10}	7.143×10^{10}
Electricity consumption reduction		31.1%
Annual performance factor	3.201	2.207

with domestic hot water operates at the domestic hot water only mode in the transition seasons of spring and autumn, and the total load of domestic hot water is 8.690×10^{9} J. The electrical energy consumed is 2.173×10^{9} J with the EER of 4.0 or so.

The air conditioning load is about 1.293×10^{11} J in a year. From the load and outdoor air temperature hour by hour and the performance of the inverter heat pump, the electrical energy consumed is 4.310×10^{10} J by the traditional heat pump.

For the heat pump with domestic hot water, there are 1.293×10^{11} J of air conditioning load and 1.964×10^{10} J of domestic hot water load in the summer and winter, which consume 4.707×10^{10} J of electrical energy.

For the same air conditioning load and domestic hot water load in a year, the traditional inverter heat pump plus electric water heater system consumes 7.143×10^{10} J electrical energy, but the inverter heat pump with domestic hot water system consumes only 4.924×10^{10} J. The total energy consumptions are 4.924×10^{10} and 7.143×10^{10} J for the new system and the traditional system, respectively, which shows a 31.1% energy saving compared with the traditional heat pump plus electric water heater. The APF values are 2.207 and 3.201 for the traditional system and the new heat pump system, respectively. Therefore, the new system is an efficient method of effective energy utilization.

5. Conclusions

A new scheme of inverter air source heat pump system operated all year round with domestic hot water is presented, and the thermodynamics analysis and economic comparison are executed as well.

A preheater and a reheater of domestic hot water are equipped at the outlet of the compressor and the inlet of the thermal expansion valve. A part of the condensing heat is recovered to heat the domestic hot water when the room needs cooling, or it will be discharged to the outdoor environment lavishly. When the room needs no cooling and no heating, the heat pump system can make domestic hot water only with the efficiency of 4.0 or so, while the efficiency is no more than

1.0 by using an electric water heater. By these two main reasons, 31.1% of the electrical energy is saved in a year, and the annual performance factor is improved from 2.207 to 3.201 by recovering the waste condensing heat of the heat pump system.

Further study on the optimal design and control strategy will be reported in other papers.

Acknowledgements

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