Analysis of economic and environmental benefits of a new heat pump air conditioning system with a heat recovery device

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Abstract. The paper designs a new wind-water cooling and heating water conditioner system, connects cooling tower with heat recovery device, which uses cooling water to completely remove the heat that does not need heat recollection, in order to ensure that the system can work efficiently with higher performance coefficient. After the test actual engineering operation, the system's maximum cooling coefficient of performance can reach 3.5. Its maximum comprehensive coefficient of performance can reach 6.5. After the analysis of its economic and environmental, we conclude that the new system can save 89822 kw per year. It reflects energy-saving and environmental benefits of the cold and hot water air conditioning system.

1. Introduction
The present worldwide energy shortage pushes people to explore ways to save energy and improve the coefficient of utilization of energy. According to different levels of energy use, 43% -70% of energy are mainly lost in the form of waste heat [1]. The air conditioning condensing heat accounts for a large proportion in the waste heat. The refrigerator takes in heat in its lower position and it releases heat in its higher position. The condensed heat of its discharge is the sum of endothermic energy and its input power. The condensed heat is \((1 + 1 / \text{COP})\) times of the cooling capacity. The condensed heat of the compressed chiller is about 1.3 times of the cooling capacity and about 2.5 times of an absorption-type chiller [2]. In the air conditioning season, due to the high temperature, the air conditioning’s condensed temperature can reach over 45°C. Meanwhile, people do not have a high requirement on hot water. Generally, the water about 40 °C can meet the bath requirements. To this end, the use of the air conditioner’s condensed heat to heat water can reduce thermal pollution. It can also reduce the hot water cost in summer [3].

2. A basic scheme of air-conditioning condenser heat recovery
2.1. Traditional heat pump system for heat recovery
The traditional heat pump system for heat recovery is generally air source heat pump system for heat recovery. It is combined with the heat pump technology and condenser heat recovery technology. It has improved the conventional air source heat pump unit. It adopts air-cooled and water-cooled composite condensation technology. It connects the plate heat exchanger with the air-cooled condenser. The condensed heat is recovered to produce the domestic hot water. The principle of this system is shown in Figure 1 [4]. When the heat pump is working, the high temperature and high pressure refrigerant gas which is discharged from the compressor firstly passes through the plate heat
exchanger. It spreads some heat to the domestic hot water, and then it enters the condenser. In this way, the temperature of the refrigerant is greatly reduced and the condensing temperature is reduced. Therefore, it has improved the operational coefficient of the machine. In addition, the released heat of the condenser changes with the air conditioning cooling load. However, changes of the air conditioning cooling load and domestic hot water load are not synchronized. Therefore, generally it needs to install hot water storage device [5].

![Figure 1](image)

**Figure 1.** The Principle diagram of the air source heat pump unit with heat recovery

### 2.2. The new heat pump system for heat recovery-the wind and chilled and hot water air conditioning system

In operation of the traditional heat pump system for heat recovery, when the tank temperature meets the set requirements, the pump which supplies water to the heat recovery machine stops working. Then the refrigerant’s condensed heat are all made by the air-cooled condenser. However, the air-cooled cooling effect is not good. The high condensed temperature makes that the COP of the system is low. The use of water-cooled air-conditioning heat recovery system must achieve the heat supply in winter. It must uses the ground-source heat pump. The system is complex and expensive. Therefore, the traditional air-cooled heat recovery heat pump system is only efficient in producing domestic hot water. However, the traditional water-cooled system is difficult to achieve the heat cycle in winter. Therefore, the new heat recovery heat pump system is designed, which is a winter-based and hot and cold water air conditioning system. The principle of this system is shown in Figure 2. The heat recovery device is connected to the cooling tower. In the operation of cooling in winter, it will not need the heat recovery part. The air-cooled condenser completely stops working. The whole system is a water-cooled heat pump air conditioning system. It reduces the system's condensation temperature. It also increases the degree of supercooling. It can ensure that the system’s operation is in the high efficiency ratio. It aims to achieve the purpose of energy saving and environmental protection. In winter, it can be adjusted through the four-way steering valve and other valves. The system can produce heat and hot water. The compressor outputs high temperature and high pressure refrigerant vapor. It firstly enters the plate heat exchanger, which can heat domestic water. Then it enters the
indoor shell and tube type of condenser (it is used as the evaporator in summer). It can heat air conditioning hot water.

The system has two different operating modes [6]: In summer, the cooling air conditioner also shares the hot water mode. In this mode, the valves 6, 7, 10 are closed. The pump 13 is closed. Other valves and water pumps are open. In this mode, the water-cooled condenser, that is the heat recovery unit, absorbs the air-conditioning condensed heat of to produce domestic hot water. The outdoor air-cooled heat exchanger 1 is closed. When the tank temperature rises to a certain extent, the valve 8 and the pump 12 are closed. The valves 6, 7 and the pump 13 are opened. When the tank temperature rises to a certain temperature or without the need for heat recovery, the water-cooled condenser can not completely cool the system. It even can not cool the system. When the compressor’s exhaust pressure and exhaust temperature are too high, you can open the cooling tower. I can continue to cool the refrigerant in a water-cooled manner. The process that the refrigerating fluid goes: compressor 3 → heat reclaiming device → four-way diverter value → electromagnetic value → expanding value → indoor heat exchanger → four-way diverter value → compressor 3. In winter, the heating air conditioner also shares the hot water mode. In this mode, the valves 6, 7, 11 are closed and the pump 13 is closed. Other valves and water pumps are open. The high temperature and high pressure refrigerant steam by the compressor firstly enters the plate heat exchanger 19. It can heat hot water. Then it enters the indoor plate heat exchanger 2. It can heat air-conditioning hot water.

In winter, the cooling tower is not open. The operation of the system is the same as the traditional air conditioning system, which combines with cooling, hot water and hot supply(Figure 1). Therefore, this paper focuses on the summer cooling and producing hot water running mode.

3. Practical engineering applications
3.1. The introduction to the system
For an office building with the heat recovery system in Guangzhou, its total construction area is 8229 m2. Its total air-conditioning area is 5266.56 m2. The air-conditioning area accounts for 64% of the total construction area. The building’s air conditioning system’s total cooling load is 600kW. It chooses two CXAH120 model air-source heat pumps. Each cooling capacity is 305kW. The cooling input power is 104.2kW. It uses four highly efficient scroll compressors and the refrigerant is R407c. The freezing water system chooses two water pumps with 5kW water pump. The cooling water system chooses a cooling towel. Its rated power is 4kW. It also uses a 5Kwde pump. It uses the Nanda Automation software to monitor and adjust the entire system. It collects the system’s operating data on time. The original system’s control interface is shown in Figure 3.

3.2. Experimental transformation of the new system’s applications
The office building’s heat recovery air source heat pump system is installed with a cooling tower, a cooling water pump and an electric valve. It can achieve the complete operation of the water source heat pump air conditioning system. In cold supply season, it has the function to cool and make hot water. In hot supply season, it has the function to heat and make hot water. The new system, or the air-based and hot and cold water air conditioning system’s control interface is shown in Figure 4. In Guangzhou, the outdoor dry temperature is 35℃. Its indoor control dry-bulb temperature is 26-28℃ and its relative humidity is 45%-65%. In the operation of the system, the hot water supply flow remains unchanged. The hot water supply’s inlet temperature will change. It can cause changes in temperature of the output hot water and changes in system performance coefficient. The function of the heat recovery type heat pump system is different from that of the ordinary heat pump system. Therefore, this paper defines the performance coefficient of the system for use in analysis [4].

- The air-conditioning performance coefficient COPa= the cooling (heating) capacity/ the input power of the complete machine
- The comprehensive performance COPa+w=( the cooling (heating) capacity +the heat of the domestic hot water)/ the input power of the complete machine

Ten different temperatures are selected to have a test, they are 33.5℃, 36.0℃, 37.8℃, 39.8℃, 41.6℃, 44.2℃, 46.3℃, 49.2℃, 51.5℃, and 53.0℃, the operating results are shown in the figure 5~6[6].

Figure 3. The air source heat pump system with Heat recovery

Figure 4. The new system—the wind and chilled and hot water air conditioning system
For comparison of Fig. 5 and Fig. 6, the maximum refrigeration coefficient of the system 1 is 2.2. Its average refrigeration system coefficient is 2.13 and its maximum comprehensive performance coefficient is 4.5. And its average comprehensive performance coefficient is 3.6. The maximum refrigeration coefficient of the system 2 is 3.5. Its average refrigeration system coefficient is 3.06 and its highest comprehensive performance coefficient is 6.5. Its average comprehensive performance coefficient is 5.57. After the system 2 is installed with the cooling tower, it can do heat recovery for the water source heat pump. Compared with the traditional heat recovery air source heat pump system, the system's performance coefficient have been improved to a certain degree. It has achieved a certain degree of energy saving and environmental protection function[6].

3.3. Economic analysis of the new system

3.3.1. Economic analysis of the summer condition--Air-water Cooled Hot-water Air-Conditioning System.

The super-heat degree of the system is 5℃, the evaporation temperature is 4℃, the condensing temperature is 40℃, and the super-cooling degree is 5℃. So it can be obtained by calculating with refrigerant physical properties software, coolpack:

- Cooling capacity of unit mass: \( q_0 = h(1) - h(4) = 402.37 - 289.62 = 112.75 \text{kJ/kg} \)
- Mass flow rate of refrigerant: \( M_r = \text{Chiller cooling capacity}/q_0 = 305/112.75 = 2.71 \text{kg/s} \).
- Theoretical power consumption of the compressor:
  \[ P = M_r h(2) - M_r h(1) = 2.71(432.05 - 402.37) = 80.43 \text{kw} \]
- Theoretical COP:
  \[ \text{COP} = \frac{\text{Chiller cooling capacity}}{\text{Total equipment power}} = 305/(80.43 + 4 + 5 + 5 + 5) = 3.07 \]
- Air-water Cooled Hot-water Air-Conditioning System:

  Power consumption=Annual total load/COP=0.75×305×3000/3.07=223534.2KWh

Notes:
  0.75—Simultaneity Usage Coefficient
  305—Cooling capacity of the system
  3000—Annual cooling days
  3.07—COP of Air-water Cooled Hot-water Air-Conditioning System
3.3.2. Economic analysis of the summer condition—Triple supply system of cooling, hot-water and heating.

If there is no cooling tower system in summer, that is to simplify an air-source heat pump system, then how much is COP? The analysis is as follows: the super-heat degree of the system is 5℃, the evaporation temperature is about 4℃, the condensing temperature is 46℃, and the super-cooling degree is 3℃, and the expression of the system cycling on the pressure enthalpy diagram is shown in figure 7. So it can be obtained by calculating with refrigerant physical properties software, coolpack:

- Cooling capacity of unit mass: \( q_k = h(1) - h(4') = 402.37 - 265.92 = 136.45 \text{kJ/kg} \)
- Mass flow rate of refrigerant: \( M_r = \frac{\text{Chiller cooling capacity}}{q_k} = \frac{305}{136.45} = 2.24 \text{kg/s} \)
- Theoretical power consumption of the compressor: \( P = M_r (h(2') - h(1)) = 2.24 \times (452.46 - 402.37) = 112.20 \text{kw} \)
- Theoretical COP: \( \text{COP} = \frac{\text{Chiller cooling capacity}}{\text{Total equipment power}} = 305/(112.20 + 5 + 5 + 8.4 + 8.4) = 2.19 \)
  Notes: 8.4KW is the rated power of condenser fan
- Annual power consumption: \( P = \frac{\text{Annual total load}}{\text{COP}} = 0.75 \times \frac{305 \times 3000}{2.19} = 313356.16 \text{KWh} \)
  Notes: 0.75—Simultaneity Usage Coefficient
  600—Cooling capacity of the system.
  3000—Annual cooling days
  2.19—COP of the triple supply system of cooling, hot-water and heating

The above data clearly shows that, electricity saving is 313356.16 - 223534.2 = 89822 kWh, which means that the air-water cooled air conditioning system can save 89822 kWh per year compared with the triple supply system of cooling, hot-water and heating. If it is the average 1 yuan per Kwh, then it can save a nearly 90000 yuan for a year. The investment of system with cooling tower can be recovered in the first year, with the excellent economic benefits.

3.3.3. Analysis of the environmental benefits in the summer condition.

According to the statistics of National Bureau, it needs 0.36 kg standard coal per kWh, so 89822 kWh electricity requires a total of 32336 kg standard coal, while the combustion of 32336 kg standard coal will produce the pollutants in column 6.

If it is the gas power plant, check the relevant specifications: the calorific value of gas is 36.22 MJ/m3, the efficiency is 60%, so the unit mass required for natural gas is 36.22 * 0.6 = 21.732 MJ/m3.
And 89822 kWh electricity required 14879 m³ natural gas, while the combustion of 14879 m³ natural gas will generate the pollutants shown in column 5.

If it is the fuel power plant, check the relevant specifications: the calorific value of heavy oil is 40MJ/kg, the efficiency is 50%, so the unit mass required for natural gas is 40 * 0.5= MJ/kg. And 89822 kWh electricity requires 16167kg heavy oil combustion, while burning 16167kg heavy oil will produce the pollutants shown in column 8.

![pollutant discharge with different energy](image)

Figure 8. pollutant discharge with different energy (CO₂ not listed)

It optimized EERs of the system through the exploration and study of the air-water cooled hot-water air-conditioning system, to achieve the significance of energy saving and environmental protection, and meet the requirements of the current society, which will bring certain economic and environmental benefits in the practical engineering.

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