Field test investigation of a double-stage coupled heat pumps heating system for cold regions

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Abstract

This paper reports a double-stage coupled heat pumps (DSCHP) heating system, which couples air source heat pump (ASHP) and water source heat pump (WSHP) together. The system is presented for the first time in open literature with the objective to improve the working condition and heating performance of the ASHP under cold environment. A practical project in Beijing firstly installed this system and field test has been performed for one month. The test results indicate that the DSCHP system can be smoothly and efficiently used for heating in cold regions. Compared with the traditional ASHP heating system, the operating characteristics of the DSCHP heating system are greatly improved, demonstrating that the system can offer considerable application potential in cold regions.

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1. Introduction

Air source heat pump (ASHP) heating system has two primary advantages: high-energy efficiency and little environmental pollution [1]. However, until now, it has been mainly used only in central and southern parts of China [2–4]. With its application area extending northward and outdoor air temperature dropping [5,6], the volumetric efficiency of compressors and mass flow rate of refrigerants will decrease and the compression ratio will greatly increase [7]. Then, the unexpected outcomes for the ASHP unit will appear, namely poor compression condition, unreliable heating capacity or even shutdown of the machine, which restrict the popularization of ASHP.

Considerable attention has been paid to improve the applicability of ASHP in cold regions. The multi-stage combined refrigeration or heat pump heating systems are
generally applied when the temperature span between the condenser and evaporator is large \([8,9]\). Some measures, such as enlarging outdoor heat exchanger areas and enhancing the outdoor fan capacity, or utilizing auxiliary electric heating device have also been adopted in the existing projects \([10]\). In Canada, Sami and Tulej developed a combined cycle fully integrated air/air heat pump (CFIA) system \([11]\). The CFIA system using environmentally sound
refrigerant blends combines the proven efficiencies of heat pump technologies with heat regenerative technologies to bring the efficient heating/cooling system with capabilities to produce domestic hot water. Laboratory and field test showed that the CFIA yielded a satisfied COP even at outside temperature of $-15 \, ^\circ C$. In Japan, Yamagami developed a new kind of ASHP with a kerosene-fired burner either placed in the indoor unit or under the evaporator to improve the performance of ASHP in low ambient temperature [12]. The packaged ASHP using a scroll compressor which varies the rotary speed with the heating load and has liquid injected inlets was proven to work smoothly even under low ambient temperatures of $-10$ to $-20 \, ^\circ C$ [13,14]. In China, Ma developed a scroll compressor with supplementary inlets for ASHP [15]. In low ambient temperature, the refrigerant from the condenser is injected into the compression chambers via the inlets. So the compression process is improved. The studies on a prototype revealed that this kind of ASHP worked very well at ambient temperatures as low as $-15 \, ^\circ C$. Manufacturers such as Dunham-Bush, Trane, Westinghouse, Daikin, Hitachi and others all developed special products of ASHP for cold climate [16]. However, most of the above measures are time-consuming and technique-demanding. In addition, great changes may happen in configuration of the ASHP unit.

In this paper, a new kind of heating system, namely the double-stage coupled heat pumps (DSCHP) heating system, is put forward, which couples conventional ASHP and WSHP together. The two operating modes work alternately in the new system, without any changes in configuration of the ASHP unit. The schematic of the two operating modes and theoretical analysis of DSCHP is also explained in detail. This system was firstly installed in a practical project in Beijing and tested in the field for 1 month. The test results verify that DSCHP can be safely and efficiently used for heating in cold regions.

### 2. DSCHP

#### 2.1. Schematic of DSCHP

As shown in Fig. 1, DSCHP can operate in two different modes. One is single-stage (SS) mode working in the moderate climate. In this case, the heating capacity of ASHP can meet the heating requirement. The ASHP supplies hot water at 40–50 $^\circ C$ for terminal users by itself, just in the same way as the conventional ASHP system. Water circulating pump 2 offers the circulating power for the terminal water loop. The other is double-stage (DS) mode working in the cold climate. In this time, heat is upgraded stage by stage. The whole system consists of ASHP (first stage), water circulating pump 1 (middle loop), WSHP (second stage), water circulating pump 2 and fan-coil units or floor heating system (terminal users). In the first stage, ASHP supplies hot water at about 10–20 $^\circ C$, which is used as the low temperature heat source for WSHP. Then, WSHP can supply the hot water at about 40–50 $^\circ C$ for the terminal users. Therefore, the working condition of ASHP and the performance of the whole system is improved. Moreover, the two transferable operating modes enable the DSCHP system well adapt to the variety of the heating load. Water circulating pump 1 and 2 offer the power for the middle water loop and terminal loop, respectively. Operating modes switch is controlled by the solenoid valve a, b, c and d. Flow direction of the hot water is directed by the solid arrow in Fig. 1.
2.2. Analysis of DSCHP

In order to see how the working condition can be improved for ASHP in DS operating mode, thirteen northern large cities in China are selected to make a primary analysis. The outdoor design temperatures (\(t_0\)) for winter air conditioning of the selected cities are all below \(-5^\circ\text{C}\).

The hot water supply temperature is set up in three different values, which are 50, 20 and 13 \(^\circ\text{C}\), respectively. The first one is always used in the SS mode, and the other two used in the DS mode. The reciprocating compressor with R22 is supposed to be applied in the above cases. As shown in Table 1, in the SS mode, the machine will run with \(n_k\) above 8.0 in 10 cities (77% of the selected 13 cities), which is the limit line for the reciprocating compressor in practical use. And it will run with \(\eta_v\) below 0.5 in eight cities (62% of the selected 13 cities), which indicates that ASHP in these regions will work with low mass flow rate. Thus, in this mode, more than 70% of Chinese northern cities cannot directly use ASHP for heating in winter. However, in the DS mode, DSCHP can run smoothly with the \(n_k\) below 8.0, and \(\eta_v\) above 0.53 in all selected cities. Both the compression condition and the heating ability can be kept in a satisfying level, which draw sharp contrast with the SS mode.

3. Field test

3.1. Project description

The newly developed heating system was first applied in a building complex with an area of 2200 m\(^2\), which situates in Fenghuang Ling natural beauty spot located in the northwest suburb of Beijing, China. The tested building consists of 17 guest rooms, 12 office rooms and some other rooms, such as meeting room, entertainment hall, dining hall and garage.

The whole heating system is composed of a DSCHP system and a floor heating system. The first stage of the DSCHP system contains one ASHP unit equipped with two reciprocating compressors. Each compressor has six cylinders. And the numbers of working compressors and cylinders are controlled automatically. Thus, through the regulation of ASHP and WSHP, the whole system can adapt to the variety of the heating load in the two operating modes.

3.2. Field test parameters and apparatus

To get the believable information of the DSCHP system, the parameters are tested as follows:

- Hot water supply and return temperature.
- Water flow rate.
- Outdoor and indoor air temperature.
- Intaking and discharging temperature of compressor.
- Condensing and evaporating pressure of ASHP and WSHP.
- Power consumed by ASHP and WSHP.

The daily energy efficiency ratio (EER) of the DSCHP system can be expressed as:
In the SS operating mode, heat output and power input of the system can be determined as:

\[ Q_{hs} = M_w C_{pw} (t_g - t_h) \]  (2)

\[ W_s = W_a + W_t \]  (3)

In the DS operating mode, heat output and power input of the system can be determined as:

\[ Q_{hd} = M_{wd} C_{pw} (t_g - t_h) \]  (4)

\[ W_s = W_a + W_t + W_w + W_{mp} \]  (5)

In the DS operating mode, the water circulating pump 1 is only used in the DS mode, so its electricity input is involved in the total power input.

The locations of relevant sensors are shown in Fig. 2 and Table 2 gives the specifications of the field test apparatus.

4. Results and discussion

Field test lasted one month during the heating season from 12/15/03 to 1/15/04. The overall operating characteristics such as ambient condition, heating effect, heating performance and the comparison between the two operating modes for the DSCHP system are presented and discussed below.

4.1. Ambient condition

The average daily outdoor air temperature of the test period is shown in Fig. 3. In the test period, the weather in Beijing is moderate. The temperature fluctuates between –6 and 6 °C (the averaged –1 °C). While, in some cases, the outdoor temperature dropped to below –10 °C, which has exceeded the value of outdoor design temperature –9 °C in Beijing. So the test results in such ambient condition can sufficiently verify the heating performance and heating effect of DSCHP.
4.2. Operating information

Daily operating information is shown in Fig. 4. In normal cases, the DSCHP system will start up with the SS mode at 5:00 pm, and shut down at 9:00 am next morning, which can take good advantage of the solar energy. In addition, the system can enjoy the preferential electricity price when it works during the night time. However, in the cloudy or extremely cold day, the operating hours will be prolonged during the daytime. When the outdoor temperature drops to as low as \(-3 \, ^\circ \text{C}\), the SS mode is alternated by the DS mode. The operating hours sum up to 520 h (72% of the whole test period), which consist of 370 h (71% of the operating hours) of the SS mode and 150 h (29% of the operating hours) of the DS mode. Though the operating hours of the DS mode is short compared with the SS mode, it plays an important role in the cold regions.

4.3. Heating effect

Average daily indoor air temperature of the test room is usually used to judge whether the DSCHP system supplied a comfortable indoor condition for the occupants. From the test data shown in Fig. 5, it can be clearly seen that even the minimum value of indoor temperature is higher than 18 \( ^\circ \text{C}\), which reaches the design criterion used in China. The maximum value is at 21 \( ^\circ \text{C}\), and the average value is at 19.5 \( ^\circ \text{C}\). Since, the building was newly painted, windows were often opened for natural ventilation, which influenced the heating effect to some extent. For example, in 1/14/04, the test room windows were opened from 10:00 am to 11:00 pm. The average daily indoor air temperature was still above 18 \( ^\circ \text{C}\). The results indicate that the DSCHP heating system offers a fairly comfortable condition to the occupants.

4.4. Heating performance of DSCHP

Heating performance of the DSCHP shown in Fig. 6 includes the heat output, power input and energy efficiency ratio (EER). The value of average daily heat output fluctuates between 124 and 186 kW, the average 153 kW. The value of average daily power input fluctuates between 33.2 and 58.2 kW, the average 49 kW. The variation of the two performance parameters are caused by the ambient condition and operating mode. With the fluctuation of these two parameters, the pattern of EER is also variable. However, all the values of EER exceed 2.5, with the average 3.2 and the maximum 4.4. The results reveal that DSCHP can be efficiently used in cold regions.

4.5. The operating characteristics comparison between the two operating modes

Figs. 7 and 8 show the working conditions and the heating performance of DSCHP before and after the operating mode switched. The data come from 4:10 to 7:30 am, 1/13/04, which contain two operating modes. One is the SS mode from 4:10 to 5:40 am, the other is the DS mode from 6:00 to 7:30 am. The switch interval of the two operating modes lasts nearly 20 min. In the two operating modes, the average outdoor air temperature is \(-6.3\) and \(-7 \, ^\circ \text{C}\), respectively, which is a fairly cold climate in Beijing. In SS mode, ASHP steadily works with two compressors and eight cylinders. No regulation processes appear. But the compression ratio reaches at 5.0 and the vibration and noise of the machine can be felt apparently. The heat output and power input of the system is 107 and 50.4 kW, respectively, and the energy efficiency ratio is only 2.1. Undesirable working conditions and heating performance appeared in this mode. In the DS mode, one of ASHP compressors experiences three start–stop periods. Each of them lasts 30 min, which contains 5 min start-time and 25 min stop-time. With the hot water supply temperature dropping to 20 \( ^\circ \text{C}\), the compression ratio of ASHP decreases to 2.6, only half of the SS mode. The vibration and noise of ASHP machine drop to the normal condition. The EER of ASHP is improved to 4.8 increased by 130% as compared with the SS mode. Meanwhile, one of the WSHP machines steadily
works with two compressors. The hot water supplied by ASHP machine at the temperature 20 °C is a proper heat source for WSHP. So the satisfying EER value 5.6 of WSHP is achieved. The heat output of the whole DSCHP system reaches 126 kW, increased by 18% as compared with the SS mode. The value of EER of the whole DSCHP system also arrives at 2.5, which is increased nearly by 20%. Therefore, the newly developed DSCHP system not only can improve the working conditions of ASHP, but also enhance the heating capacity and operating energy performance.

5. Conclusions

In this paper, a DSCHP heating system with two operating modes has been developed and primarily analyzed. The system was installed in a practical project and tested for 1 month. The test results show that it offers the average EER up to 3.2, minimum at 2.5, and the average indoor temperature exceeds 19.5 °C, minimum at 18 °C in test period. As compared with the SS mode, the compression ratio of the ASHP decrease 50% and the EER of ASHP is improved to 4.8 increased by 130%, WSHP offers the EER up to 5.6, the heating capacity of the system increased by 18%, the EER of the DSCHP system increased by 20%. This verifies that the operating characteristics of the DSCHP system are greatly improved, and it may offer considerable application potential in cold regions.

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