Study on Optimal Operation of Boiler-assisted Air Source Heat Pump Heating System

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Abstract. An electric boiler assisted air source heat pump heating system is used in a residential heat exchange station in Shijiazhuang for heating. However, in the actual operation process, there is a problem that the heating demand cannot be met. This paper studies the heating system. The results show that the problems are mainly manifested in two aspects: on the one hand, the operation strategy of heat exchange station is unreasonable; On the other hand, because of the close arrangement of heat pump units, the array cold island effect is produced, which affects the heating operation. Put forward a reasonable operation scheme for two aspects, and provide a reference case for central heating operation of air source heat pump in northern China.

1. Introduction
For a long time, energy and environmental problems have been the survival problems that all countries in the world pay special attention to. [1] Especially when China experienced a period of rapid economic development, fossil energy was widely used, which made our government and people pay more and more attention to environmental protection and sustainable development. Therefore, our government put forward the "3060 target" in 2021 to promote the emission reduction of greenhouse gases with carbon dioxide as the main component. In order to achieve the "3060 target", it is necessary to use clean energy instead of traditional fossil fuels. With the support of the national "coal-to-electricity" policy, air source heat pump has gradually entered people's field of vision. Compared with traditional fossil energy, air source heat pump has the advantages of cleanness, high efficiency and no pollution. In recent years, air source heat pump has been widely used in the Yangtze River Basin [2]. In some northern areas, due to economic problems, the heating demand cannot be effectively met, so it is necessary to add auxiliary heat sources for auxiliary heating. However, in the actual operation process, there will also be problems such as low operation efficiency and inability to meet the heating demand.

2. Project Overview
This project is located in a residential area of Shijiazhuang City, China. With a total building area of 130,650 m\textsuperscript{2} and a building area of 101,000 m\textsuperscript{2} to be heated. Electric boiler assisted air source heat
pump heating system is used for heating, and the heating end is radiator. This project is a residential building, which needs heating all day.

The equipment is arranged in the equipment room in the northeast corner of the community, and the heat pump is arranged in the west side of the equipment room. See table 1 below for details of equipment:

Table 1. Equipment parameter table.

| Equipment                  | Quantity | Air source heat pump | Electric boiler | Heat storage tank | Circulating pump of primary network | Secondary network circulating pump | Secondary network makeup pump | Plate heat exchanges |
|----------------------------|----------|----------------------|-----------------|-------------------|-------------------------------------|-----------------------------------|-------------------------------|----------------------|
|                            | 74 sets  | 1 set                | 1 set           | 2 sets (one for use) | 2 sets (one for use) | 2 sets (one for use) | 1 set |                      |
| Heating capacity           | 64.5KW   |                      |                 |                   |                                    |                                   |                               |                      |
| The COP is                 | 3.3      |                      |                 |                   |                                    |                                   |                               |                      |
| Rated power                | 2800KW   |                      |                 |                   |                                    |                                   |                               |                      |
| Volume                     | 143t     |                      |                 |                   |                                    |                                   |                               |                      |
| Flow rate                  | 89t/h    |                      |                 |                   |                                    |                                   |                               |                      |
| Head                       | 18m      |                      |                 |                   |                                    |                                   |                               |                      |
| Flow rate of secondary     | 500t/h   |                      |                 |                   |                                    |                                   |                               |                      |
| make up pump               |          |                      |                 |                   |                                    |                                   |                               |                      |
| Flow rate                  | 6.3T/h   |                      |                 |                   |                                    |                                   |                               |                      |
| Head                       | 48m      |                      |                 |                   |                                    |                                   |                               |                      |
| Area                       | 160m²    |                      |                 |                   |                                    |                                   |                               |                      |

3. System Operation

3.1. Operation Status

At the beginning and end of the heating season, when the outdoor temperature is high, the air source heat pump is directly connected to heat users. With the decrease of outdoor temperature and the increase of heat load, the number of air source heat pumps will be gradually increased until all air source heat pump units are in operation. In the middle stage of heating, when the outdoor temperature is low, when 74 air source heat pump units are turned on and still can't meet the heating demand, the electric boiler and the heat storage tank are put into operation, and the water supply and return of the heat storage tank are indirectly connected with the heat users through plate exchange, while the electric boiler mainly heats the water in the heat storage tank at night to realize the energy-saving operation of "shifting peak and filling valley" [3]. The process flow chart is shown in figure 1 below.

During the operation of the heating system, there is a problem that the heating demand cannot be met, which is manifested in the following aspects: low temperature of supply and return water and insufficient heat supply.

After the actual field investigation, some data of the system operation in December were collected, and the basic data are as follows:
Table 2. Partial operation data of heating system in December.

| Time  | Outside temperature (°C) | Relative humidity (%) | Two-network traffic (m³/h) | Water supply temperature of secondary network (°C) | Secondary network backwater Temperature (°C) | Heat (GJ/h) | Unit operation Line quantity |
|-------|--------------------------|-----------------------|-----------------------------|---------------------------------------------------|---------------------------------------------|------------|----------------------------|
| 10:33 | 1.5                      | 38.00%                | 465                         | 43.7                                              | 37.9                                        | 11.17      | 48                         |
| 11:27 | 2.2                      | 36.00%                | 461                         | 43.7                                              | 38.0                                        | 11.04      | 48                         |
| 12:19 | 4.5                      | 20.60%                | 459                         | 43.1                                              | 37.8                                        | 10.08      | 36                         |
| 14:42 | 5.5                      | 17.00%                | 462                         | 42.8                                              | 37.4                                        | 10.29      | 36                         |
| 15:14 | 4.0                      | 18.80%                | 466                         | 42.8                                              | 37.4                                        | 10.49      | 36                         |
| 4:57  | -3.1                     | 64.60%                | 466                         | 44.4                                              | 38.7                                        | 10.96      | 59                         |
| 5:48  | -2.0                     | 57.60%                | 464                         | 44.0                                              | 38.5                                        | 10.77      | 59                         |
| 6:48  | -0.2                     | 61.40%                | 465                         | 43.8                                              | 38.4                                        | 10.41      | 59                         |
| 7:45  | -2.5                     | 62.60%                | 463                         | 43.7                                              | 38.0                                        | 10.75      | 59                         |
| 3:14  | -2.2                     | 64.70%                | 462                         | 43.5                                              | 38.2                                        | 10.10      | 59                         |
| 4:02  | -2.3                     | 61.70%                | 460                         | 43.2                                              | 37.8                                        | 10.40      | 59                         |
| 5:09  | -2.1                     | 59.10%                | 462                         | 42.8                                              | 37.4                                        | 10.40      | 59                         |
| 6:33  | -1.9                     | 67.10%                | 459                         | 42.5                                              | 37.3                                        | 9.80       | 59                         |

Figure 2 is obtained by drawing the collected data into a line chart and comparing it with the theoretical heat load.

As can be seen from figure 2:
(1) The experimental heat supply fluctuates little with the change of outdoor temperature, and hardly changes. Guess may be related to the short time difference of data collection. Data collection is done in two or three consecutive days at different time periods, and the step size of heating regulation may be in days, so there is little change in heating quantity.

(2) The experimental heat supply does not meet the requirements of heat load at all, and even the actual heat supply does not reach 60% of the theoretical heat supply.

### 3.2. Cause Analysis

Through field investigation and communication with operators, the problems in system operation are mainly caused by the following two reasons:

(1) Arrangement of air source heat pump unit array. There are 74 heat pump units in the heating system. Limited by the site, the distance between the units is close, and the distance between the longitudinal units is only 0.44m. The cold air discharged from the evaporator of the unit after heat exchange will accumulate in the center of the unit array, forming the cold island effect [4]. In the process of operation, even the outdoor temperature was -5℃, while the central temperature of the unit array reached -14℃. Moreover, the cold island effect will be aggravated with the decrease of outdoor temperature, which will lead to the decline of unit heating performance.

(2) There are problems in the operation strategy of heating system. The heating system adopts the operation mode of "large flow and small temperature difference", and the regulation mode adopts quality regulation. When all the air source heat pumps are turned on, the electric boiler and heat storage tank will be turned on for auxiliary heating only when the return water temperature on the user side is lower than 36℃. The figure below shows the change of the number of heat pump units with outdoor temperature.

During the operation of heating system, air source heat pump is the main heat source for heating. With the decrease of outdoor temperature, the heat load increases, but the heating capacity of a single heat pump unit is decreasing, so it is necessary to increase the number of heat pump units to meet the heating demand. Therefore, there will be a critical outdoor temperature value, which makes all heat pump units turn on just to meet the heating demand. After calculation, this theoretical critical temperature value is 2.5℃. See the next section for the calculation method.

As can be seen from figure 3, when the outdoor temperature is lower than 2.5℃, theoretically all 74 units of air source heat pump have been put into operation, but in actual heating operation, when the outdoor temperature is reduced to -3℃, there are still many units that are not in operation. As a result, the heat supply is insufficient to meet the heating demand.

### 3.3. Summary

In this section, through the analysis of field survey data and communication with operators, we found two main reasons for the problems in operation: on the one hand, the unreasonable operation strategy;
on the other hand, because of the limited site, the tight arrangement of units aggravated the array cold island effect.

4. Solutions

In view of the operation problems of the heating system, it is necessary to calculate the whole heating system. First, calculate the heat load of the heating building. The design heat load calculated by the heating index is the maximum design heat load, and the calculation of the heat index already includes the total heat loss during the transportation process of the heating network. The calculated heat load is calculated according to equation (1).

\[ Q_{\text{max}} = q \times A \]  

Type: \( Q_{\text{max}} \) —— heating design heat load, \( KW \);
q —— heating heat index, 80% of heating buildings do not have external insulation layer, take \( 60W / m^2 \) [5];
A —— heating building area, is 101,000 \( m^2 \).

Through calculation, the heating design heat load is as follows:
\[ Q_{\text{max}} = q \times A = 60 \times 101000 = 6.06 \times 10^6W = 6.06 \times 10^3KW \]

The heating system adopts quality regulation, the designed temperature of supply and return water is, and the design flow of circulating water at the user side is calculated according to the following formula: \( 65^\circ C/50^\circ C \), and the design flow of circulating water at the user side is calculated according to equation (2).

\[ G = k \times \frac{aQ_{\text{max}}}{t_s - t_h} \]  

Type: G —— design flow rate of circulating water at user side, t/h;
k —— Margin coefficient, dimensionless, taking 1.1;
a —— Constant, taking 0.86;
t_s —— Design water supply temperature, \( ^\circ C \), taking 65\( ^\circ C \);
t_h —— Design backwater temperature, \( ^\circ C \), taking 50\( ^\circ C \).

Through calculation, the design flow of circulating water at the user side is as follows:
\[ G = k \times \frac{aQ_{\text{max}}}{t_s - t_h} = 1.1 \times \frac{0.86 \times 6.06 \times 10^3}{65 - 50} = 382.19t/h \]

It can be seen that the circulating water flow in actual operation is more than 1.2 times of the designed circulating water flow, so the actual temperature difference between supply and return water is smaller than the designed temperature difference between supply and return water.

The heating capacity and COP of the air source heat pump unit will be affected by the outdoor temperature and the outlet water temperature of the unit. Ju Chen is adopted in this paper [6]. In the study, the data are fitted to calculate the heating capacity of a single unit. See equation (3):
\[ \varepsilon_q = 193.7 - 111.9\varepsilon_s - 493\varepsilon_s - 10.46\varepsilon_s^2 + 265.5\varepsilon_s\varepsilon_r + 371.6\varepsilon_s^2 + 100.6\varepsilon_s^3 - 300\varepsilon_s^2\varepsilon_r + 163.6\varepsilon_s\varepsilon_r^2 - 178.8\varepsilon_r^3 \]  

Type: \( \varepsilon_q \) —— The ratio of relative heating capacity of heat pump unit, dimensionless;
\( \varepsilon_s \) —— The ratio of relative water supply temperature of heat pump unit, dimensionless;
\( \varepsilon_r \) —— The ratio of the heat pump unit to the outdoor temperature, dimensionless;

Among them: \( \varepsilon_q = \frac{Q}{Q_k} \), \( \varepsilon_s = \frac{t_s}{t_s} \), \( \varepsilon_r = \frac{t_w}{t_w} \).
Type: $E$ —— Relative to rated working condition at outdoor temperature. [7] Ratio, in which the rated working conditions are: $t_w=7^\circ C$, $t_g=45^\circ C$. The actual heating capacity of a single unit in the project is: $Q_k=64.5$ kW.

Through equation (4), the number of open units at any outdoor temperature that can meet the heating demand can be calculated.

$$Q_{max} \times \frac{t_n - t_w}{t_n - t_{we}} = n \times Q_k$$ (4)

Type: $t_n$ —— indoor design temperature, $^\circ C$, taking 18$^\circ C$;
$t_{we}$ —— Outdoor design temperature, $^\circ C$, taking -8$^\circ C$;
$n$ —— Number of heat pump units to be started, the maximum is 74;
$Q_k$ —— heating capacity of a single heat pump unit, kW.

Therefore, under the condition of meeting the heating demand, the relationship table of the number of open units corresponding to any outdoor temperature is obtained. Because in actual operation, the units are divided into 13 groups, including 4 groups with 5 units and the remaining 9 groups with 6 units. The units in each group start and stop at the same time, so the relationship table is as follows:

### Table 3. Relationship between outdoor temperature and number of open units.

| Outdoor temperature/$^\circ C$ | 18 ~ 16.5 | 16.5 ~ 15.0 | 15.0 ~ 13.7 | 13.7 ~ 12.3 | 12.3 ~ 10.9 | 10.9 ~ 9.5 | 9.5 ~ 8.3 | 8.3 ~ 7.1 | 7.1 ~ 6.0 | 6.0 ~ 5.0 | 5.0 ~ 4.1 | 4.1 ~ 3.3 | 3.3 ~ 2.5 | 2.5 ~ -8 |
|-----------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Number of open groups       | 1        | 2        | 3        | 4        | 5        | 6        | 7        | 8        | 9        | 10       | 11       | 12       | 13       |
| Number of open units        | 5        | 10       | 15       | 20       | 26       | 32       | 38       | 44       | 50       | 56       | 62       | 68       | 74       | 74       |

| Outdoor temperature/$^\circ C$ | 8.3 ~ 7.1 | 7.1 ~ 6.0 | 6.0 ~ 5.0 | 5.0 ~ 4.1 | 4.1 ~ 3.3 | 3.3 ~ 2.5 | 2.5 ~ -8 |
|-----------------------------|----------|----------|----------|----------|----------|----------|----------|
| Number of open groups       | 8        | 9        | 10       | 11       | 12       | 13       |
| Number of open units        | 44       | 50       | 56       | 62       | 68       | 74       |

To solve the problem of unreasonable operation, the original operation mode is changed, and the number of air source heat pump starts, stops and starts is operated according to the above table 3. When the outdoor temperature is lower than 2.5$^\circ C$, the electric boiler and the heat storage tank are started, and the peak power is used first, which is not repeated here.

In view of the cold island effect, because there are a large number of heat pumps used in the heating system, but the space is small, it is not practical to increase the distance between units in the array to improve the influence of the cold island effect. So, learn from Lei Yanjie and others [8]. Put forward the way of installing baffle in heat pump unit array to improve the influence of array cold island effect on the operation of heating system.
The figure below shows the simulated temperature field without baffle and with baffle respectively, in which the row spacing of heat pump units is 0.5m, and all of them are the temperature distribution rephotograph of the axial section of the second row of 10 heat pump units.

From the comparison of the following two figures, it can be seen that the temperature near the heat pump evaporator in the middle area is obviously lower than that at both ends when the baffle plate is not installed, while the temperature distribution near the heat pump evaporator in the middle area is more uniform after the baffle plate is installed. Effectively alleviate the influence of cold island effect.

Figure 4. Cloud diagram of temperature distribution without baffle.

Figure 5. Cloud diagram of temperature distribution with baffle.

5. Conclusion
Taking the electric boiler-assisted air source heat pump heating system of a heat exchange station in Shijiazhuang as an example, there are two main problems in the heat exchange station: on the one hand, the unreasonable operation strategy and on the other hand, the arrangement of unit array. Aiming at the problem of operation strategy, the number of heat pumps can be calculated between outdoor temperature zones. In view of the array arrangement problem, under the condition that the spacing between units cannot be increased due to the limited site, baffles can be installed. The above two methods are not only applicable to the residential area, but also provide effective cases for the operation of air source heat pump central heating system in northern China.

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