Optimizing Energy Consumption Strategy of Water-loop Heat Pump

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Abstract. In order to study the influencing factors of energy consumption of water-loop heat pump system, the optimal loop-water temperature strategy is proposed. The multi-variable building load is transformed into circulating water energy only related to water temperature. From Carnot cycle to think of the optimal loop-water temperature strategy, the original water temperature control method is changed. This paper shows that there is a unique circulating water temperature, which can minimize the overall energy consumption under certain building load conditions.

1. Introduction

The energy problem has become the main problem facing the world today [1]. China is the largest developing country in the world, and such problems are particularly acute. The report of Sun Jiasen [2] shows that in almost all provinces in eastern China, there are problems of inefficient energy allocation and severe energy shortage. The use of renewable energy [3, 4] and energy recovery technology [5, 6] has become an important way to solve it. Heat pump technology [7] is an energy-saving device that uses recovery and conversion technology to apply energy from air, water and soil to an air-conditioning system, effectively reducing conventional energy consumption. Therefore, it is particularly important to study heat pump [8-10] and its technology [11-13].

Water-loop heat pump (WLHP) air-conditioning system is a kind of air-conditioning system, which is connected in parallel by a set of two-pipe water loops, consisting of a large number of water-source heat pump units with different forms. This system can effectively utilize the residual heat in the room. The schematic diagram of the water-loop heat pump system is shown in Figure 1. Since the heat and cold of different rooms in the system cannot completely offset each other, the circulating water gains or loses heat, causing the loop water temperature to rise or fall. The loop water temperature should be maintained at 16°C ~ 32°C [14].

At present, the research focus of WLHP is energy-saving. Howell and Zaidi [7] proposed a method to determine whether the heat recovery potential of a building would allow the system to operate without a boiler and prove maximum heat recovery rate and energy efficiency of various buildings through simulation. Chang [15] used the theory of circulating water level to study the influence of different load ratios on the running energy consumption of WLHP. Waddicor [16] proposed new insights into the performance of water-water heat pumps under partial load. Experiments have found that the deterioration of energy performance mainly occurs during system startup, and the system will suffer additional efficiency losses due to the short cycle of temperature control under low load. In specific application, Lian [17] compared the energy consumption of WLHP with that of traditional air-
conditioning, and concluded the suitable areas for using WLHP in China. Barone [18] get the real-time energy, economic and environmental assessment of WLHP system by analyzing the performance of WLHP through a dynamic simulation model specially designed for building-water-loop heat pump system analysis. Chen [19] evaluated the operation and control conditions of the system by analyzing the two-year field test data of a high-rise apartment in Beijing, and comprehensively evaluated the energy-saving characteristics of the system. Yuan Shui [20] proposed the effect of circulating water temperature on system energy consumption, and [21] optimized the optimal circulating water temperature theory. Simulations of building and air conditioning systems have found that optimal water temperatures minimize system energy consumption.

When researching the WLHP system, the following issues should also be addressed: First, the temperature control of the circulating water is to turn on the cooling tower equipment or the heat source equipment when it reaches its maximum or minimum value, or to control loop water temperature in real time. Second, a factor needs to be determined to measure the energy consumption of the system.

In order to solve the above problems, this paper takes circulating water as the research object, and uses the nature of the heat pump to convert the building load into circulating water energy. The strategy of this paper regards the system at a certain moment as the steady state and finds the optimal circulating water temperature (Figure 2). In this paper, simulation software is used to simulate the building and water loop heat pump system in Nanjing, which provides data support for the new theory.

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**Figure 1. Schematic of a WLHP system.**

**Figure 2. Optimal water temperature control process.**
2. Carnot cycle
The theoretical basis for finding the optimum temperature of the WLHP is derived from the Carnot cycle (Figure 3).

Analysis of a single heat pump: In the cooling mode, the water temperature in the heat pump is lower than the indoor temperature, so the indoor is a heat source, the heat pump unit is a cold source, and the indoor air transfers heat to the circulating water. The Carnot cycle thermal efficiency formula is \( \eta_\text{c} = 1 - \frac{T_2}{T_1} \), and the thermal efficiency is only related to the temperature of the cold heat source. \( T_1 \) is the indoor temperature is a fixed value, the method of increasing the thermal efficiency is only to reduce the loop water temperature \( T_2 \) as much as possible. The lowest loop water temperature is 16°C, so when \( T_2 \) equals 16°C, the heat pump achieves the maximum thermal efficiency. Similarly, in the heating condition, when \( T_2 \) is equal to the maximum temperature 32°C of the circulating water, the maximum thermal efficiency is obtained.

Analysis of all heat pumps in the system: Each heat pump has a circulating water temperature that maximizes the thermal efficiency. In actual operation, some of the heat pumps are in cooling mode and some are in heating mode, so there is an optimum temperature between 16°C and 32°C for all heat pump systems. Analysis of the WLHP system:

The control of the circulating water needs to be combined with cooling tower and boiler, and the cold heat source needs to consume additional work. The optimum temperature for all heat pumps is not necessarily the optimum temperature for the WLHP system.

In this paper, the power equation of heat pump, cooling tower and boiler is established to determine whether there is an optimal temperature, and the binary search algorithm is used to find it.

3. Optimum circulating water temperature model
The power of heat pumps, cooling tower and electric boiler is only related to \( T_{lp} \), so only \( T_{lp} \) is the independent variable in the expression of total power.

\[
POW_{\text{total}}(T_{lp}) = \sum POW_{hp}(T_{lp}) + POW_{ct}(T_{lp}) + POW_{bo}(T_{lp})
\]

Equation (1) is continuous on \([T_{lb}, T_{ub}]\), so \( POW_{\text{total}}(T_{lp}) \) has its minimum and maximum values according to the extremum theorem.

\[
\frac{d^2POW_{\text{total}}}{dT_{lp}^2} = \sum \frac{d^2POW_{hp}}{dT_{lp}^2} + \frac{d^2POW_{ct}}{dT_{lp}^2} + \frac{d^2POW_{bo}}{dT_{lp}^2} \geq 0
\]
According to Yuan’s analysis [21], the total power is non-negative to the second derivative of $T_{lp}$.

The local minimum of $POW_{total}(T_{lp})$ on $(T_{lh},T_{ah})$ is also the global minimum.

In previous studies, for the dynamic change of energy consumption of the system, factors affecting the building load itself should be considered, such as outdoor temperature and humidity, building envelope structure and so on. However, some factors are difficult to measure, and the dynamic changes of building load are difficult to analyze in real time, resulting in complex modeling of energy consumption in research systems and difficulty in returning data in real time. Using the reverse energy theory to transform the building load into circulating water energy, the multivariate function of the change of building load is transformed into a single variable function of water temperature, which greatly simplifies the construction of the system energy consumption operation model, so that the system can be based on the load of the building. This way can change the water temperature in real time to achieve optimal system. The whole system regards water temperature as the only variable, which connects energy consumption and building load. The complex problem of adjusting room cooling and heat is transformed into the minimum energy consumption value of balancing loop water temperature. In the quasi-static process:

1. The water temperature remains unchanged, and the energy of circulating water reaches balance, and it is always in the optimal circulating water temperature operation state.
2. When the water temperature rises and the indoor cooling load increases, the increased load is calculated according to the circulating water energy equation, the optimal water temperature is found, the cooling tower power is adjusted, and a new equilibrium state is reached.
3. The water temperature drops, the indoor heat load increases, the increased heat load is calculated, the optimal water temperature is found, the boiler power is adjusted, and a new equilibrium state is reached.

4. Evaluation of optimal control model for reverse energy loop water temperature

In order to study the performance of the optimal loop water temperature $T_{lp}$ control strategy, the best method in this paper is compared with the traditional temperature control strategy (When $T_{lp} \leq 16^\circ C$, heat is injected into the circulating water circuit by opening the boiler; when $T_{lp} \geq 32^\circ C$, the cooling tower is turned on to remove the heat of the circulating water circuit.). In order to compare, it is necessary to use the same working conditions in the case of building load and outdoor weather, so computer simulation is used for analysis.

4.1. Building model

The simulation software TRNSYS is used to model the building and WLHP system. TRNSYS is a very flexible, vivid and modular transient process simulation software. The modeled building has three floors, each of which has the same structure and is divided into inner and outer zones. The inner zone of each layer is $1128.96 \text{ m}^2$, and the outer zone of each layer is $1411.2 \text{ m}^2$ (Figure 4). The outer zone WLHP has a cooling capacity of 55 kW and a heating capacity of 60 kW; the inner zone WLHP has a cooling capacity of 25 kW and a heating capacity of 30 kW. The electric boiler is 500 kW, the cooling tower air volume is $63200 \text{ m}^3/h$, and the fan power is 4 kW. Building ventilation is handled uniformly by a centralized air handling unit and is outside the scope of this paper. Building model air conditioning time is from 8:00 to 18:00 on Monday to Friday. The simulation time step of the model is 10 minutes, and the simulation lasts for one year.

4.2. Simulation results

This paper chooses 4328-4338 hours for analysis (Figure 5-7). Table 1 shows the specific values of system energy consumption per hour. In previous studies, there was a lack of indicators that could directly assess the energy consumption of buildings. COP only indicates the relationship between energy consumption and refrigeration capacity of heat pump unit, but it cannot express the energy
consumption of WLHP system. In order to better evaluate the performance of the WLHP system, this paper defines a new evaluation factor—load energy consumption ratio $\theta$. $\theta$ is the ratio of building cooling and heating load to total energy consumption of WLHP system (Figure 8). The larger the load-energy ratio of water-loop system, the more energy-saving the system will be. On the contrary, it will not save energy. Table 2 shows the energy consumption ratio per hour under two control modes.

Through simulation experiments, it is verified that there is an optimal water temperature in the operation of the WLHP, so that the WLHP system has the lowest energy consumption. Compared with the traditional control mode, the optimal water temperature control mode of the building model can save 37.12% under cooling condition.

Figure 4. Indoor load and outdoor temperature. Figure 5. Loop water temperature comparison.

Figure 6. POW comparison. Figure 7. System energy consumption comparison.

Figure 8. Load energy consumption ratio comparison.
Table 1. System energy consumption.

| Time | Traditional control (kW) | Optimal control (kW) |
|------|--------------------------|----------------------|
| 4329 | 25.40                    | 20.14                |
| 4330 | 43.15                    | 32.86                |
| 4331 | 46.66                    | 31.06                |
| 4332 | 50.20                    | 27.14                |
| 4333 | 41.66                    | 24.49                |
| 4334 | 44.09                    | 24.65                |
| 4335 | 53.57                    | 31.28                |
| 4336 | 51.52                    | 35.96                |
| 4337 | 49.70                    | 28.78                |
| 4338 | 49.35                    | 29.92                |
| Total| 455.30                   | 286.29               |

Table 2. Load energy consumption ratio $\theta$.

| Time | Traditional control | Optimal control |
|------|---------------------|-----------------|
| 4329 | 6.90                | 8.68            |
| 4330 | 6.69                | 8.97            |
| 4331 | 6.29                | 9.68            |
| 4332 | 6.01                | 11.36           |
| 4333 | 6.02                | 10.54           |
| 4334 | 5.81                | 10.43           |
| 4335 | 5.70                | 9.89            |
| 4336 | 5.72                | 8.24            |
| 4337 | 5.75                | 10.11           |
| 4338 | 5.70                | 9.86            |
| Average | 6.06                | 9.78            |

5. Conclusions
This paper draws conclusions through analysis:

1. The building load can be converted into circulating water energy, which is useful for analysing changes in load. The change of circulating water energy can accurately reflect the change of load, and provide a basis for finding the optimal temperature.

2. Load energy consumption ratio $\theta$ can well represent the energy consumption of each system to solve its cooling and heating load under the same building load, and can intuitively compare the energy saving of each system.

References
[1] Goodman J and Marshall J P 2018 Problems of methodology and method in climate and energy research: Socialising climate change? Energy Research & Social Science (vol 45) pp 1-11.
[2] Sun J S, Li G and Wang Z H 2018 Optimizing China’s energy consumption structure under energy and carbon constraints Structural Change and Economic Dynamics (vol 47) pp 57-72.
[3] Liu J X 2019 China's renewable energy law and policy: A critical review Renewable and Sustainable Energy Reviews (vol 99) pp 212-219.
[4] Huang S Y, Liu Z Y and Zhang C Y 2018 The problem study of district energy system in Shanghai, China Energy Procedia (vol 145) pp 542-548.
[5] Szega M and Czyż T 2019 Problems of calculation the energy efficiency of a dual-fuel steam boiler fired with industrial waste gases Energy (vol 178) pp 134-144.
[6] Madani H, Claesson J and Lundqvist P 2013 A descriptive and comparative analysis of three
common control techniques for an on/off controlled Ground Source Heat Pump (GSHP) system. 

[7] Howell R H and Zaidi J H 1990 *Analysis of heat recovery in water-loop heat pump systems.* 

[8] Adrián M B, Carlos M R, Joaquín N E and et al 2018 Optimisation of high-temperature heat pump cascades with internal heat exchangers using refrigerants with low global warming potential *Energy*(vol 165)pp 1248-1258. 

[9] Bai T, Yan G and Yu J L 2019 Thermodynamic assessment of a condenser outlet split ejector-based high temperature heat pump cycle using various low GWP refrigerants *Energy*(vol 179)pp 850-862. 

[10] Guo J J, Wu J Y, Wang R Z and et al 2011 Experimental research and operation optimization of an air-source heat pump water heater *Applied Energy*(vol 88)pp 4128-4138. 

[11] Guo P Y, He M C, Zheng L G and et al 2017 A geothermal recycling system for cooling and heating in deep mines *Applied Thermal Engineering*(vol 116)pp 833-839. 

[12] Li C F, Cleall P J, Mao J F and et al 2018 Numerical simulation of ground source heat pump systems considering unsaturated soil properties and groundwater flow *Applied Thermal Engineering*(vol 139)pp 307-316. 

[13] Zou D Q, Ma X F, Liu X S and et al. Experimental research of an air-source heat pump water heater using water-PCM for heat storage *Applied Energy*(vol 206)pp 784-792. 

[14] Li X G 1998 Thermal performance and energy saving effect of water-loop heat pump systems with geothermal *Energy Conversion and Management*(vol 39)pp 295-301. 

[15] Chang R, Yu Q D and Zhu N 2012 Part-Load Ratio Research on Energy Consumption of Heat Pump System; proceedings of the Asia-pacific Power & Energy Engineering Conference. 

[16] Waddicor D A, Fuentes E, Azar M and et al 2016 Partial load efficiency degradation of a water-to-water heat pump under fixed set-point control *Applied Thermal Engineering*(vol 106)pp 275-285. 

[17] Lian Z W, Park S R, Qi H N 2005 Analysis on energy consumption of water-loop heat pump system in China *Applied Thermal Engineering*(vol 25):pp 73-85. 

[18] Barone G, Buonomano A, Forzano C and et al 2016 WLHP Systems in Commercial Buildings: A Case Study Analysis Based on a Dynamic Simulation Approach. 

[19] Chen C, Sun F-L, Feng L and et al. Underground water-source loop heat-pump air-conditioning system applied in a residential building in Beijing *Applied Energy*(vol 82)pp 331-344. 

[20] Yuan S and Grabon M 2010 Energy Analysis and Optimization of a Water-Loop Heat Pump System *Journal of Thermal Science and Engineering Applications*(vol 2)pp 1005-1008. 

[21] Yuan S and Grabon M. Optimizing energy consumption of a water-loop variable-speed heat pump system *Applied Thermal Engineering*(vol 31)pp 894-901.