Energy Proceedings
Vol 40, 2024
ISSN 2004-2965

Investigation of an office building geothermal heating system integrating heat pump and energy storage

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ABSTRACT

In this study, taking an office building in Xi'an city as the research object, the heat load of the office building has been simulated using DeST. The rate of heat extraction from a 2000 m closed-loop geothermal well has also been simulated using COMSOL. The influences of the mass flowrate on the heat extraction rate and the average outlet temperature have been discussed. Combined with the downhole heat exchanger model, the heat pump model, and the thermal energy storage model, an integrated numerical simulation model for office building heating is established. The model is used to investigate the influence of different energy storage ratio on the system total cost, based on which the optimal energy storage ratio is determined. The results obtained from this study provide theoretical basis for improving geothermal energy utilization.

Keywords: geothermal heating system, integrated model, thermal energy storage, heat pump, closed-loop heat extraction, energy storage ratio

1. INTRODUCTION

In the era of carbon peak and carbon neutrality, energy substitution and transformation are challenges around the world. Building is the main part of the energy consumption, where the heating system contributes the most to the total building consumption. Therefore, reducing heating consumption is one of the effective ways to save energy.

As a kind of renewable energy with huge underground reserves, geothermal energy has a very large space for utilization. The ground source heat pump (GSHP) systems which have the advantages of high efficiency have been widely used. The depth of the closed-loop geothermal well can be above 2000 m, where there is a higher heat extraction rate, other than the traditional GSHP system, in which the depth of the borehole is less than 300 m. Besides, the reinjection and environmental pollution are difficult to solve for the traditional method of extracting geothermal hot water. The downhole heat exchanger with a closed water cycle does not require reinjection, which only occupies a small footprint, and has higher heat extraction power than the traditional method of extracting geothermal, hence, it is a clean and efficient technology to utilize geothermal energy.

The integrating system of shallow ground source heat pump and energy storage has been studied extensively at home and abroad. Kim [1] et al. studied the operation characteristics and energy saving potential of a vertical closed-loop ground source heat pump system combined with energy storage tank in an office building, and found that adding energy storage tank could give the soil in the heat exchange area more time to supplement heat, reduce the running time of the ground source heat pump under partial load, and improve the system efficiency. Bonamente [2] et al. added an energy storage tank to the ground source heat pump system and compared and analyzed the influence of two energy storage materials on the system performance. The results show that both water and phase change material have higher system performance than the system without energy storage tank, but the phase change material energy storage tank is smaller than the water energy storage tank. Junxin Lu [3] et al. introduced a system composed of the GSHP and energy storage tank. Through tests and simulations, it was found that the composite system saved operating costs and improved performance coefficient compared with GSHP system.

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

At present, the research and utilization of the medium and deep GSHP systems and energy storage technology are becoming more and more mature, but there are few researches on integrating them. Wei Wang [4] established the heat transfer analytical model of closed u-well heat exchanger. And the simulation modelof the whole medium and deep ground source heat pump heating system is constructed. Using this model, the influence of different circulating flow combinations on the system operation efficiency under different load demand is discussed, and the optimal strategy of medium and deep ground source heat pump heating system for long-term operation is obtained. Jiewen Deng [5] et al. showed the outlet water temperature of heat source of the medium and deep geothermal heat pump system is obviously higher than other conventional heat pump systems, the energy efficiency of the system is improved, and the system is suitable for space heating of residential buildings. In order to make full use of the advantages of them, a geothermal heating system integrating heat pump and energy storage was proposed to realize the time-space energy efficiency transfer of the user's heat source and increase the system reliability. Through reasonable system design and based on time-of-use electricity prices, the combination of the two technologies is of great significance for realizing efficient and clean heating for buildings.

2. MODELS

The equipment involved in the geothermal heating system integrating heat pump and energy storage include closed-loop geothermal well, heat exchanger, heat pump, water pump and thermal energy storage. Therefore, the mathematical models of each part of the equipment were established respectively for analysis and research. A simplified scheme of the geothermal heating system integrating heat pump and energy storage is shown in Fig. 1.

2.1 The closed-loop geothermal well model

The closed-loop geothermal well model is established and calculated the heat extraction rates using COMSOL. The flow direction of the fluid from the annular cavity to the inner pipe is employed in the proposed model, which is more conducive to extracting heat. The diameter of the inner pipe and the outer pipe are 0.11 m and 0.1778 m respectively. The closed-loop geothermal well here is about 2000 m deep. And the ground surface temperature is set to be 15.6 °C.

2.2 The above-ground system model

2.2.1 The heat exchanger model

The logarithmic mean temperature difference method (LMTD method) was used to model the heat exchanger. The heat transfer rate of fluid is given by:

$$Q_{ex} = kA\Delta T_m = m_h C(T_{h,in} - T_{h,out}) = m_c C(T_{c,out} - T_{c,in})$$

where k is the heat transfer coefficient (kW/(m^2·K)); A is the heat transfer area (m^2); ΔT_m is the logarithmic mean temperature difference (K); C is the specific heat capacity of water (C=4.19 kJ/(kg·K)); m_h , m_c are the mass flowrate of hot water and cooling water respectively (kg/s); $T_{h,in}$, $T_{h,out}$ are the inlet and outlet temperatures were respectively measured for hot water(K); $T_{c,in}$, $T_{c,out}$ are the inlet and outlet temperatures were respectively measured for cooling water(K).

2.2.2 The heat pump model

The steady state physical model of a water-water heat pump unit is established. It is assumed that the energy is conserved throughout the whole cycle.

The heat transfer rate in the evaporator is given by:

$$Q_{eva} = m_r(h_{e,out} - h_{e,in}) = m_{ew} C(T_{ew,in} - T_{ew,out})$$

where m_r is the mass flowrate of working fluid (kg/s); $h_{e,in}$、$h_{e,out}$ are the inlet and outlet enthalpy of the working fluid, respectively (kJ/kg); m_{ew} is the mass flowrate of water in the evaporator (kg/s); $T_{ew,in}$、$T_{ew,out}$ are the inlet and outlet temperatures of water in the evaporator, respectively (K).

The heat transfer rate in the condenser is given by:

$$Q_{con} = m_r(h_{c,in} - h_{c,out}) = m_{cw} C(T_{cw,out} - T_{cw,in})$$

where $h_{c,in}$, $h_{c,out}$ are the inlet and outlet enthalpy of the working fluid, respectively (kJ/kg); m_{cw} is the mass flowrate of water in the condenser (kg/s); $T_{cw,in}$, $T_{cw,out}$ are the inlet and outlet temperatures of water in the condenser, respectively (K).

The compressor power is given by:

$$W_{com} = m_r(h_s - h_{e,out}) / \eta$$

where h_s is the outlet enthalpy of the working fluid in theory (kJ/kg); the evaporator outlet parameters are consistent with the compressor inlet parameters; η is efficiency.

The expansion process is adiabatic, the inlet enthalpy of the expansion valve is equal to that of the outlet enthalpy($h_{c,out} = h_{e,in}$).

The coefficient of performance of the heat pump is given by:

$$COP = Q_{con} / W_{com}$$

2.2.3 The water pump model

In a closed water system, the head of the pump is used to overcome frictional resistance and local resistance. The power consumption of the pump is calculated by:

$$W_p = \gamma m_p H / 3600 \eta_p$$
$$H = (H_1 + H_2 + H_3) \times \alpha$$

where γ is the volumetric weight of water(γ =9.8 kg/m); m_p is the mass flowrate of water(kg/s); η_p is the pump efficiency; H is the head of pump(m); H_1 is the frictional head loss (m); H_2 is the local head loss when water flows through the equipment (m) ; H_3 is the local head loss when water flows through valves and bends (m) ; α is the margin coefficient(α = 1.1).

The relationship between the water pump head (H) and pressure loss (ΔP) is given by:

$$H = \Delta P / \rho g$$

The frictional pressure loss is calculated by Hazen–Williams Formulas [6]:

$$\Delta P_{al} = 1000L(105C_h^{-1.85} d_j^{-4.87} q_g^{1.85} f)$$

The local pressure loss is given by:

$$\Delta P_{lo} = \zeta \frac{\rho \upsilon^2}{2}$$

where L is the length of pipe (m); C_h is the Hazen–Williams coefficient(C_h =140); d_j is the inside diameter of pipe; q_g is the volume flow rate of water(m^3/s); f is the correction coefficient; ζ is the coefficient of local resistance; υ is the flowrate of water(m/s).

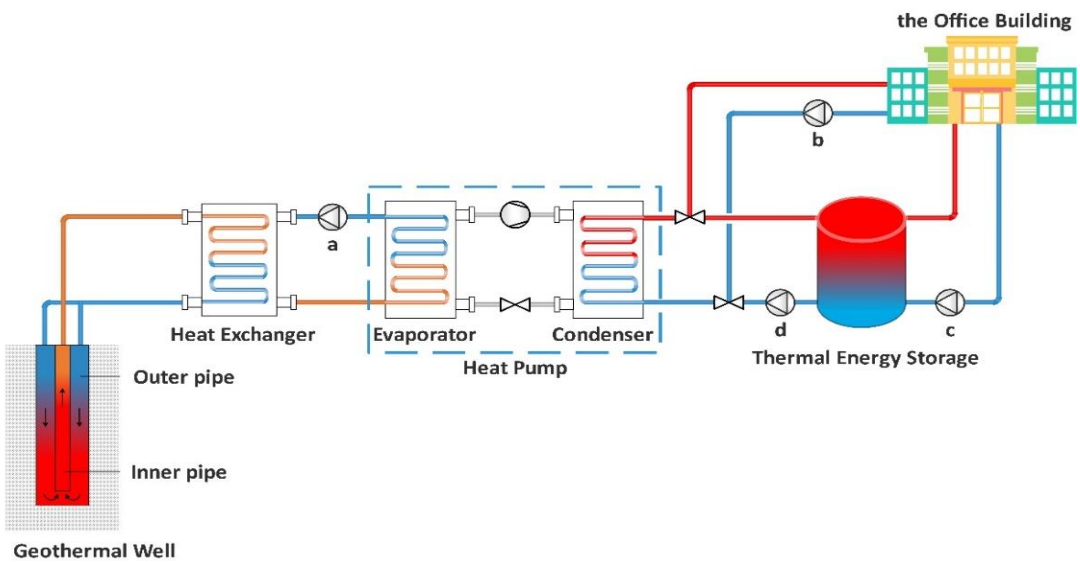

Fig. 1 The geothermal heating system integrating heat pump and energy storage

2.2.4 The thermal energy storage model

It is assumed that the internal temperature of the thermal energy storage(TES) is uniform. The hourly temperature is the average temperature, regardless of temperature gradient. The mathematical expression is obtained according to the conservation of energy, as follows [7]:

$$MC\frac{dT_\tau}{d\tau} = F_1 m_{\tau,s} C(T_{\tau,s} - T_\tau) - F_2 m_{\tau,h} C(T_\tau - T_{\tau,h}) - k_t A_t (T_\tau - T_0(\tau))$$

where M is the mass flowrate of water in the TES (kg/s); T_τ is the temperature of the TES (K); $m_{\tau,s}$ is the mass flow rate of the TES during energy storage (kg/s); $T_{\tau,s}$ is the inlet temperature of the TES during energy storage (K); $m_{\tau,h}$ is the mass flowrate of the TES during heating (kg/s);$T_{\tau,h}$ is the inlet temperature of the TES during heating (K); k_τ is the heat transfer coefficient between the water inside the TES and the surroundings of the TES (W/(m^2·K)); A_τ is the heat transfer surface area (m^2); T_0 is ambient temperature (K).

When the TES is storing heat, F_1=1 and F_2=0. Conversely, when the TES supplies heat to the building, F_1=0 and F_2=1.

2.3 Economic evaluation

The total costs are used for economic evaluation, which include the annual investment costs, the annual maintenance costs and the operating costs. The total costs can be expressed as[7]:

$$C = \frac{\Omega}{\Omega^{ann}}(C_I^{ann} + C_M^{ann}) + \sum_t^{\Omega} C_O^t$$

where C_I^{ann} are the annual investment costs; C_M^{ann} are the annual maintenance costs; C_O^t are the operating costs; Ω is the simulation period; Ω^{ann} is annual heating period.

The specific expressions are as follows:

$$C_I^{ann} = \eta_{CRF} C_{TCI}$$

$$\eta_{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1}$$

$$C_{TCI} = c_{HEX} A_{HEX} + c_{HP} Q_{HP} + c_{TES} V_{TES} + c_p W_P$$

$$C_M^{ann} = \eta_M C_{TCI}$$

$$\sum_t^{\Omega} C_O^t = \sum_t^{\Omega} (c_{ele}^t P_{ele}^t)$$

where i, n are the discount rate (i=8%), the lifetime of the system (n=20 years), respectively. C_{TCI} are total investment costs; η_M is maintenance cost rate(η_M = 1%); C_{ele}^t is electricity price; P_{ele}^t are total power consumptions, including heat pump and water pump.

3. SIMULATION RESULTS

3.1 Heat load

Taking an office building in Xi'an, with an area of 20582 m^2, as the research object. The indoor and outdoor design parameters and envelope design parameters were set, and the office building model was established in DeST, as shown in Fig. 2.

The heat load of the office building during the winter heating period was obtained by simulation (the heating period was from November 15 to March 14 of the following year). The dynamic heat load was calculated by taking the meteorological data of Xi'an into account as given in Fig. 3.

According to the simulation results, the maximum heat load in the heating period is 20772.58 kW, which appears on January 10, and the cumulative heat load demand is 1.3×10^6 kW.

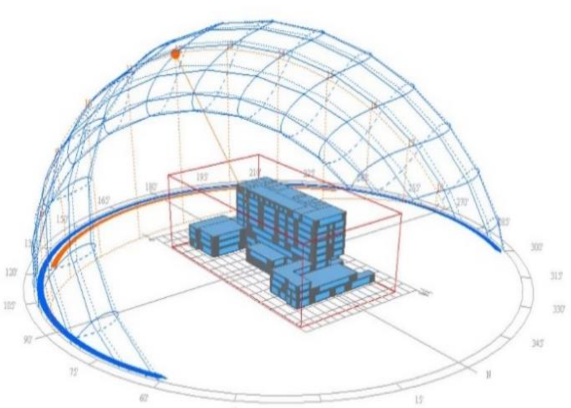

Fig. 2 The office building model in DeST

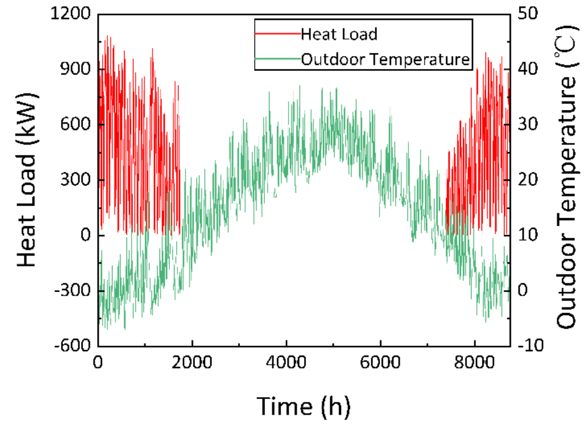

Fig. 3 Building heat load and outdoor temperature

3.2 The heat extraction rate and average outlet temperature analysis

The temperature of the inflow is set to be 17.6 °C. Fig. 4 shows the heat extraction rate and average outlet temperature of the closed-loop geothermal well under different mass flowrate conditions. It is seen that the heat extraction rate increases very small when the mass flowrate is more than 3.7 kg/s. At the same time, with the increase of the mass flowrate, the average outlet temperature decreases.

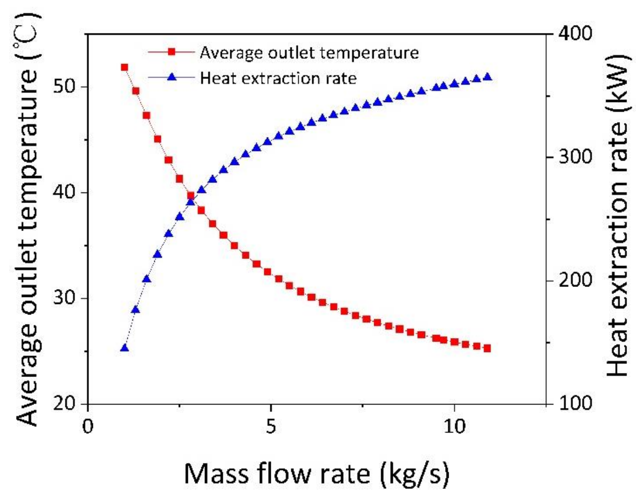

Fig. 4 The heat extraction rate and average outlet temperature variations under different mass flowrate

3.3 The influence of energy storage ratio

The simulation period is 7 days, that is, from January 6 to January 12 (168 hours), and the heating period is from 8:00 to 20:00. An operation strategy is proposed. In the valley price stage, the thermal energy of TES is stored by heat pump heating, and in the peak price period, the thermal energy heating of the TES is given priority. When the TES is individually insufficient for heating, the geothermal energy is supplemented for heating. Table. 1 and Table. 2 illustrate equipment prices and time-of-use electricity prices, respectively.

The energy storage ratio represents the ratio of the maximum heat storage capacity of TES to the average heat load in simulation period. It can be seen from Fig. 5 that the total cost of the system is significantly reduced as the energy storage ratio increases, then an upward trend after the energy storage ratio is greater than 0.64, corresponding to the total cost is the lowest cost, 2.47×10^5 CNY. Compared the benchmark system that do not connect the TES, the total costs are reduced 50%. The trend of investment costs is roughly the same as that of total costs, while the operating costs generally show a downward trend. And the operating costs of water pump and heat pump are shown in Fig. 6.

Table. 1 Equipment price parameters

Name	Price
Heat exchanger	800 CNY/m^2
Heat pump	500 CNY/kW
Pump	2000 CNY/kW
Thermal energy storage tank	1000 CNY/m^3

Table. 2 Time-of-use electricity prices

Type	Time	Price
Peak	8:00 –12:00;16:00 – 20:00	0.96 CNY/kWh
Flat	6:00 – 8:00;12:00 – 16:00; 20:00 –22:00	0.66 CNY/kWh
Valley	22:00–6:00	0.35 CNY/kWh

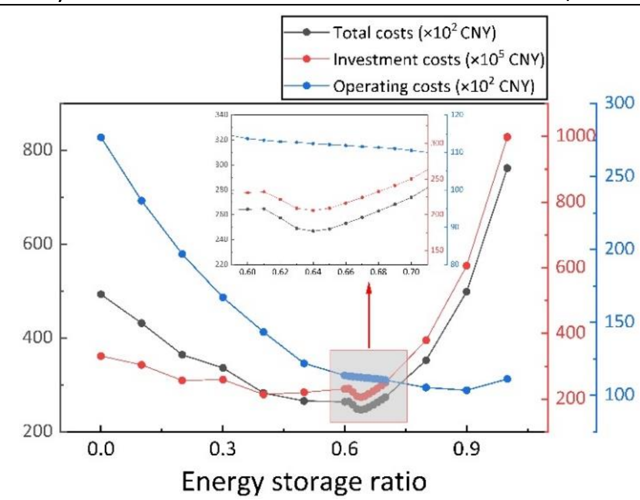

Fig. 5 The influence of energy storage ratio on costs

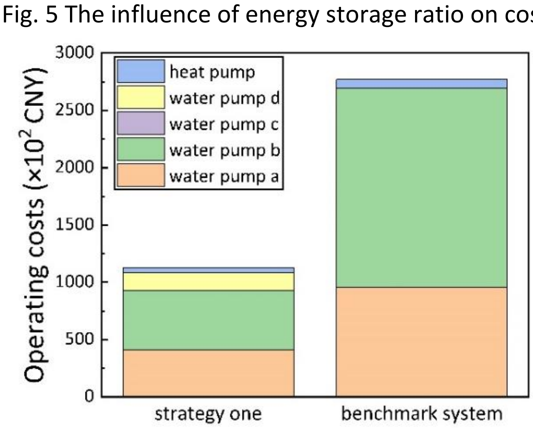

Fig. 6 The operating costs of main equipment

4. CONCLUSIONS

In this paper, the modeling method of the geothermal heating system integrating heat pump and energy storage is introduced in detail, including closed-loop geothermal well model, heat exchanger model, heat pump model, water pump model and thermal energy storage model. The DeST is used to simulate the heat load of the office building, and the load results provide a basis for the system optimization. A closed-loop geothermal well model is established by COMSOL to analyze the changes of average outlet temperature and heat extraction rate under different mass flowrates, which provide a basis for coupling with the above-ground system model. At the same time, MATLAB is used to calculate the influence of different energy storage ratio on the total costs under time-of-use electricity prices, and the optimal energy storage ratio is obtained. The main conclusions are discussed below:

(1) With the increase of the mass flowrate, the average outflow temperature decreases and the heat extraction rate increases. When the mass flowrate is greater than 3.7 kg/s, the heat extraction rate increase slowly, indicating that the mass flowrate of 3.7 kg/s has the best performance in heat production.

(2) The geothermal heating system integrating heat pump and energy storage can reduce total costs. The best energy storage ratio is 0.64.

(3) Further studies on techno-economic analysis should be carried out in using appropriate optimization algorithms to optimize the geothermal heating system integrating heat pump and energy storage.

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