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Study building heat storage operation strategy for air-to-water heat pumps connected to a residential floor heating system

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Abstract. A transient simulation model of floor radiant heating system with air-to-water heat pumps for a 100 m^2 building in the Beijing rural area was developed by using TRNSYS software, and combining the Hooke-Jeeves algorithm on the GenOpt platform, the influence of building exterior wall insulation on building heat storage strategy of the floor radiant heating system with air-to-water heat pumps was studied on the current peak and valley period electricity price. The law of the best heat-lag temperature and heat-lag time was obtained under different building exterior wall insulation method and thickness by optimizing the whole heating season operation cost.

1. Introduction

As people's requirements for building comfort have increased, floor radiant heating system with air-to-water heat pumps has become more and more popular in China.

When considering the economics of air-to-water heat pump floor radiant heating systems, it is necessary to combine local electricity prices. By utilizing the local peak-to-valley electricity price, combined with the characteristics of the thermal inertia of the heating system, a reasonable operation strategy can be formulated. On the one hand, the effect of peak-cutting and valley-filling can be realized, and on the other hand, the operation cost can be reduced.

At present, some scholars have carried out research on the operation strategy of floor radiant heating system with air-to-water heat pumps. Verhelst et al [1] used the energy storage characteristics of the air-to-water heat pump floor radiant heating system building envelope to compare the heating system operation time under different thermal comfort and operation cost weighting factors with the highest indoor thermal comfort and the lowest operation cost on the peak and valley electricity price. Xu et al [2] put forward the peak and off-peak intermittent running operation strategy and point out that the peak and off-peak intermittent running operation strategy is better than off-peak intermittent running operation by comprehensively comparing the heating room temperature and operation cost.

For the residential buildings with continuous heating in winter, in the context of China's comprehensive implementation of residential peak and valley electricity price, and encouraging residents to participate in the power shift peak-filling policy, how to use the peak and valley differential electricity prices to develop a reasonable operation strategy for the heating system. It is an urgent problem to be solved.

Taking 100 m^2 residential buildings in rural areas of Beijing as an example, this paper combines the local peak and valley period electricity price to use the building envelope structure for heat storage during the valley period. Analyzing and studying the influence of different insulation methods and thickness of the insulation layer on the heat storage strategy has great significance for practical engineering.

2. Building a model
This paper builds a model of floor radiant heating system with air-to-water heat pumps through TRNSYS [3]. The building model and the floor radiant coil model use the type56 module in TRNSYS. The accuracy of the model is determined by the parameters such as the enclosure structure, the indoor air change rate and the indoor heat source. If the above parameters are set properly, the simulation results have higher reliability.

2.1. Building model
The building model uses a type56 module from TRNSYS to simulate a single-storey rural house with a building area of 100 m^2 and a height of 3.2 m. The rural residential building located in Beijing. The architectural plane diagram of the rural residential building is shown in Figure 1.
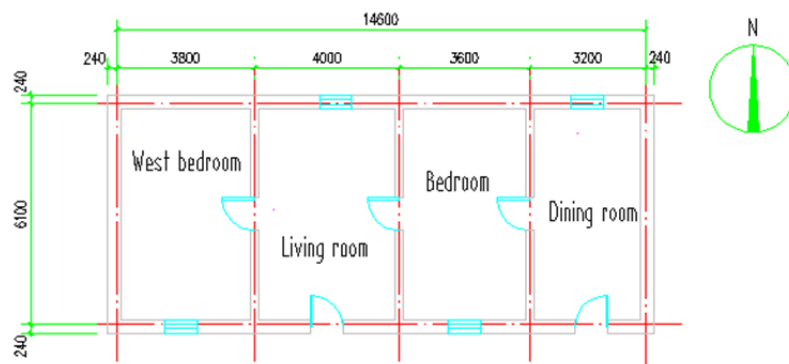

Figure 1. Architectural plane diagram of the rural residential building.

The detailed setting of the building refers to the typical rural residential buildings in the cold area in reference [4]. The ratio of south window to wall is 0.1, the ratio of north window to wall is 0.05 and air change rate is 1 1/h. The basic information of the building is shown in Table 1.

Table 1. Architectural basic information.

Structure	Coefficient of heat transfer (W m^{-2} K^{-1})
Exterior wall	1.697
Roof	0.422
Ground	0.039
Exterior window	5.68

According to the relevant regulations and requirements of "Design standards for energy efficiency of rural residential buildings", the window was transformed into a hollow window with a heat transfer coefficient of 2.8 W/(m^2·K). The floor radiant heating surface is cement, the filling layer is 60 mm concrete, and the bottom layer is provided with insulation layer. The buried pipe adopts DN20 PE pipe with a pipe spacing of 200 mm. There are four coils, including the main body of the west bedroom is 97 m, the main body of the living room is 89 m, the main body of the bedroom and the dining room are 96 m, and the other one is 95 m. The rural residential building heating coil plan is shown in Figure 2.
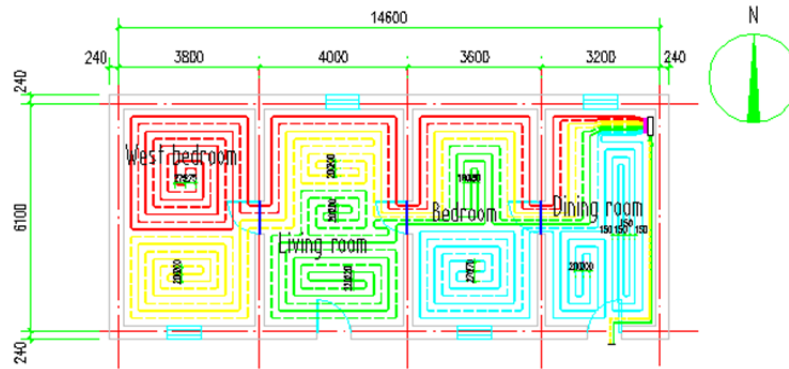
Figure 2. Heating coil plane diagram of the rural residential building.

2.2. Air-to-water heat pump model
The simulation was carried out by considering the McQuay air-to-water heat pump MACO50ER5-AE and the horizontal multistage centrifugal pump. The rated heat capacity of the heat pump unit is 14.8 kW and the rated power is 4.4 kW. The pump head is 17 m, the flow rate is 2.5 m³/h, the rated power is 0.37 kW, and the efficiency is 0.5.

The paper uses the empirical formula in the literature [5] to defrosting the heat pump unit COP (heating coefficient of performance), the performance parameters of the heat pump unit and the unit test data provided by McQuay.

$$CAP_r = -0.0001836t_o^2 - 0.0000686t_g^2 - 0.0000815t_ot_g + 0.0190017t_o + 0.0021383t_g + 0.9515673$$
$$(R^2=0.9972) \tag{1}$$
$$COP_r = -0.0000456t_o^2 + 0.0001571t_g^2 - 0.0003565t_ot_g + 0.0279493t_o - 0.0338114t_g + 2.1128644$$
$$(R^2=0.9933) \tag{2}$$

Where, CAP_r is the ratio of the performance curve heating capacity to the nominal operating condition, COP_r is the ratio of the performance curve COP to the nominal operating condition COP, t_o is the outdoor temperature, t_g is the heat pump unit outlet temperature.

When the ambient temperature is lower than 7 °C and higher than 7 °C, the COP attenuation value COP_{df} caused by unit defrosting is shown in formula (3) and formula (4).

$$COP_{df} = -0.0027(t_o - 7) + 0.1801\exp(-t_o^2/5) \tag{3}$$

$$COP_{df} = 0.1801\exp(-t_o^2/5) \tag{4}$$

2.3. Heating system model
The weather file in the model adopted the typical weather year TMY2 data file of Beijing. The floor radiant heating system with air-to-water heat pumps was built by TRNSYS, and some assumptions were made for the simulation of the actual project. The assumptions include that the heating system does not consider the effect of pressure changes on the energy efficiency of the pump and the heat loss from the unit to the coil is neglect. The TRNSYS simulation system is shown in Figure 3.

3. Influence of building insulation method and thickness on heat storage strategy
As an important part of the envelope structure, the external wall is the key factor to cut off the indoor and outdoor direct heat exchange and maintain the indoor heat and humidity environment. Analyzing and studying the influence of different insulation methods and thickness of the insulation layer on the heat storage strategy.
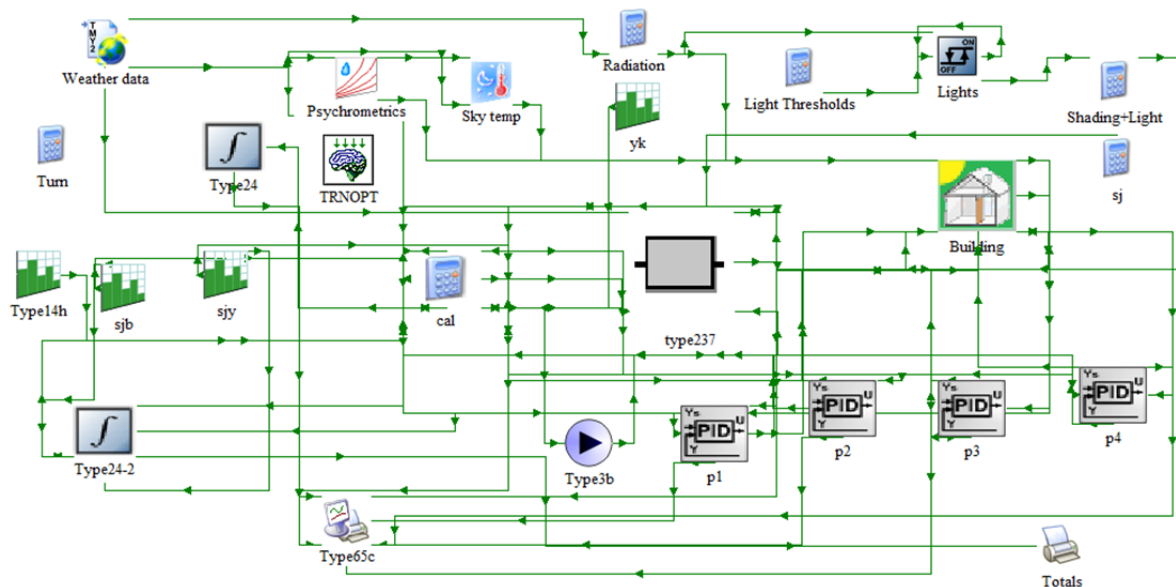
Figure 3. Simulation system by TRNSYS.

3.1. Heat storage strategy

The air-to-water heat pumps supplied water temperature is 42 °C from 6:00 am to 6:00 pm, and 40 °C from 6:00 pm to 6:00 am. By detecting the indoor temperature, the solenoid valve opening on each branch road is adjusted to ensure the indoor set temperature. There has been a lot of researches on the effect of floor temperature on thermal comfort [6, 7]. To facilitate analysis of the operation strategy, according to the relevant regulations and requirements of "Design code for residential buildings" , in this paper, the indoor temperature of each room is set to 18 °C in the non-heat storage period, the indoor temperature of the heat storage period is set to 18-22 °C (exceeding non-heat storage set temperature 0-4 °C), and the heat-lag time is within 10 hours before the end of the valley period.

3.2. Optimization process

The heat-lag temperature and heat-lag time of the heating system are optimized. To improve the calculation efficiency, the Hooke-Jeeves algorithm is used to find the optimal heat-lag temperature and heat-lag time of the heating system. When dealing with cases with a large number of experiments, Hooke-Jeeves algorithm has the advantages of fast convergence and strong adaptability. The method includes a global search and a local search using a coordinate search method, and the two methods alternately until the convergence condition is satisfied, and the point at which the objective function minimized is obtained. Under the premise of ensuring the indoor temperature, the optimized the target which operation cost of the heating season of heat pump unit and the pump is the lowest, the heat-lag temperature range is 18-22 °C, the heat-lag time range is 0-10 hours. The initial heat-lag temperature is set to 20 °C and the initial value of the heat-lag time is set to 7 hours. The peak and valley electricity price of local residents using is shown in Table 2.

Table 2. Peak and valley electricity price of local residents.

|	Time	Electricity price (yuan kWh^{-1})
Peak period	8:00am-10:00pm	0.55
Valley period	10:00pm-8:00am	0.32

There are many types of building insulation materials [8]. In China, EPS is the most common building insulation material. Therefore, in this paper, EPS is chosen as the insulation material for

exterior walls. Currently, the price of EPS on the market is 480 yuan/m^3. Under the premise of meeting "Design standards for energy efficiency of rural residential buildings" on the premise of the heat transfer coefficient of the outer wall of rural cold areas, the EPS of 6, 8, 10 and 12 cm is added to the original typical building external wall. Increasing the heat transfer coefficient of the external wall as shown in Table 3.

Table 3. Heat transfer coefficient of external wall.

Structure	Coefficient of heat transfer (W m^{-2} K^{-1})	Insulation investment(yuan m^{-2})
Exterior wall+EPS(6cm)	0.559	28.8
Exterior wall+EPS(8cm)	0.457	38.4
Exterior wall+EPS(10cm)	0.386	48
Exterior wall+EPS(12cm)	0.335	57.6

Through the Hooke-Jeeves optimization algorithm on the GenOpt software platform, the optimal heat-lag temperature and heat-lag time of different insulation methods and thicknesses under the heat storage operation strategy are found. The optimization process of the Hooke-Jeeves algorithm is shown in Figure 4.
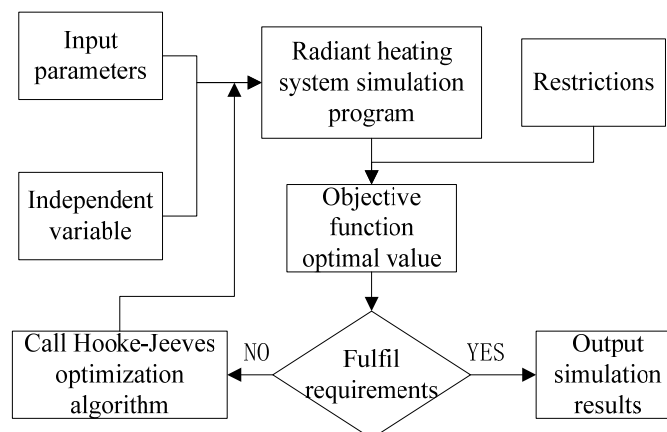
Figure 4. Hooke-Jeeves algorithm optimization flow chart.

3.3. Optimization results analysis

According to the optimization results of heat-lag temperature and heat-lag time under different external insulation thicknesses, the best storage operation cost of heating seasons with different external insulation thicknesses are obtained as shown in Table 4.

Table 4. Heating season operation cost under different external wall external insulation thickness.

External insulation thickness(cm)	Non-heat storage strategy operation cost(yuan)	Optimal heat-lag temperature(℃)	Optimal heat-lag time(h)	Optimal heat storage strategy operation cost(yuan)
6	1824	19.6	6.2	1758
8	1705	19.6	5.2	1641
10	1622	19.6	5.2	1560
12	1561	19.5	5.2	1501

As the thickness of the external insulation increases, the operation cost of the optimal heat storage strategy and the non-heat storage strategy are reduced. The external wall of the building is increased by 6-12 cm EPS external insulation. The optimal heat-lag temperature is about 19.5 ℃, and the optimal heat-lag time is about 6 hours. The optimal heat storage strategy has a cost savings ratio of about 3.7% compared to the non-heat storage strategy.

According to the optimization results of heat-lag temperature and heat-lag time under different internal insulation thicknesses, the best storage operation cost of heating seasons with different internal insulation thicknesses are obtained as shown in Table 5.

Table 5. Heating season operation cost under different external wall internal insulation thickness.

Internal insulation thickness(cm)	Non-heat storage strategy operation cost(yuan)	Optimal heat-lag temperature(°C)	Optimal heat-lag time(h)	Optimal heat storage strategy operation cost(yuan)
6	1844	19.9	7.2	1755
8	1726	19.9	7.2	1636
10	1644	19.7	6.5	1556
12	1584	19.5	5.5	1499

As the thickness of the insulation layer increases, the operation cost of the optimal heat storage strategy and the non-heat storage strategy are reduced. The external wall of the building is increased by 6-12 cm EPS internal insulation. The optimal heat-lag temperature is 19.5-20 ℃, and the optimal heat-lag time is 5.5-7.5 hours. The optimal heat storage strategy has a cost savings ratio of 4.8-5.4% compared to the non-heat storage strategy.

The operation cost savings ratio of the optimal heat storage strategy under different external wall insulation methods and thickness compared with the non-heat storage strategy is shown in Figure 5.
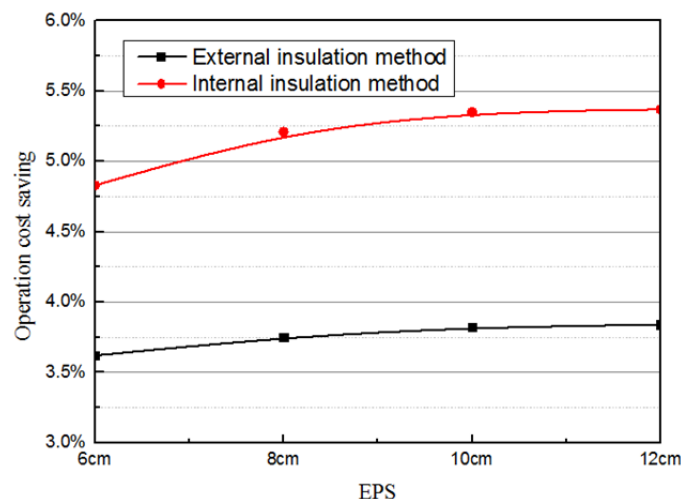
Figure 5. Proportion of operation cost savings for optimal thermal storage strategy versus non-storage strategy.

With the increase of the thickness of the insulation layer of the external wall of the building, whether it is the internal insulation method or the external insulation method, the proportion of the optimal heat storage strategy saving operation costs increases. But with the thickness of the building exterior wall insulation, the trend of saving the proportion of operation cost has also slowed down.

Compared with the external insulation, the insulation method of the internal insulation of the external wall of the building has an increased operation cost under the non-heat storage strategy. Under the optimal heat storage strategy, the external wall internal insulation method has higher potential for saving operation cost than the external insulation method.

4. Conclusions

By connecting the internal modules of TRNSYS, the calculation model of the floor radiant heating system with air-to-water heat pumps was built and the heating system heat storage strategy was optimized by the Hooke-Jeeves algorithm on GenOpt. For the rural building of 100 m^2 in the cold area, combined with the local electricity price, the EPS insulation is added to the external wall of the rural residential building.

With the increase of the thickness of the external insulation, the operation cost of the non-heat storage strategy and the heat storage strategy are both reduced, and the proportion of the operation cost savings of the optimal heat storage strategy compared non-heat storage strategy is slightly increased. The external wall of the building is increased by 6-12 cm EPS external insulation, the optimal heat-lag temperature is between 19.5 and 19.6 ℃, and the optimal heat-lag time is 5-6.5 hours. The operation cost savings ratio of optimal heat storage strategy compared non-heat storage strategy is between 3.6% and 3.9%. The building exterior wall is increased by 6-12 cm EPS internal insulation, the optimal heat-lag temperature is between 19.5 and 20 ℃, and the optimal heat-lag time is 5.5-7.5 hours, the optimal heat storage strategy is between 4.8% and 5.4% compared to the non-heat storage strategy on the operation cost savings ratio. Compared with external thermal insulation, the insulation method of building internal thermal insulation has higher potential for saving operation cost under the heat storage operation strategy.

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