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CONTROL STRATEGY OF HOUSEHOLD AIR-SOURCE HEAT PUMP- FLOOR RADIANT HEATING SYSTEM CONSIDERING THERMAL COMFORT

Lijia Du[1], Xianjun Meng [1], Xianxu Huo[2], Shupeng Li[2], Yan Qi[2], Yunfei Mu[1*]

1 Key Laboratory of Smart Grid of Ministry of Education (Tianjin University), Tianjin, China;

2 Tianjin Power Research Institute, State Grid Tianjin Power Company, Tianjin, China

ABSTRACT

With heat pump(HP) heating getting popular in China, a control strategy for air source heat pump-low-temperature hot water floor radiant heating system (AHPFHS) is required to reduce the operating cost of the it. Model of household AHPFHS was established based on the characteristics of the equipment. The forecast data from weather stations was utilized to build the residential building thermal load model based on the heat balance equation. A rolling optimization control method was proposed. Considering thermal comfort of the customers, the indoor temperature set-point was scheduled for the lowest operating cost of the AHPFHS. A typical case was built to validate the feasibility of the proposed method. Numerical studies show that the proposed control method is able to effectively reduce the operating cost of the system.

Keywords: rolling optimization, indoor temperature set-point, air source heat pump, floor radiant heating system, building thermal load model

NONMENCLATURE

Parameters and constants	
T_e	ambient temperature(℃)
T_{s1}	water temperature at HP outlet(℃)
q_1	volume flow for water at the inlet of HP (m^3/h)
q_{2max}	maximum volume flow for water at the inlet of RFHS (m^3/h)
q_2	volume flow for water at the inlet of RFHS (m^3/h)
ρ_w	density of water (kg/m^3)
c_w	specific heat capacity of water (kJ/(kg/k))
T_{s2}	water temperature at RFHS inlet(℃)
T_{r2}	water temperature at RFHS outlet(℃)
T_{set}	indoor temperature set-point(℃)
T_z	actual indoor temperature(℃)
dT_{up}/dT_{low}	absolute value of difference between the maximum/minimum temperature allowed and T_{set}
ρ_a	air density of the building(kg/m^3)
c_a	air specific heat capacity of the building (kJ/(kg/k))
V_Z	air volume of the building(L)
Parameters and constants	
Q_{hps}	static output of the air source HP, (kW)
COP	coefficient of performance of the air source HP
P_{comp}	power of compressor(kW)
P_{vent}	power of fan (kW)
P_{cp1}	power of HP circulating pump(kW)
P_{cp2}	power of heating network circulating pump(kW)
P_t	real-time power of AHPFHS(kW)

1. INTRODUCTION

Building energy conservation is in urgent need. In 2014, buildings accounted for 30.6% of the total global terminal energy consumption. In that year, the total energy consumption of buildings in China equaled to 814 million tons of standard coal, accounting for 19.12% of the country's total energy consumption. At present, building energy consumption has been juxtaposed with industrial energy consumption and transportation energy consumption, making the three large energy consumers in China. Air source HP units are applied worldwide in recent decades, thanks to their advantages of high efficiency, low emission, low cost and etc[1]. However, it is difficult for conventional air conditioning systems to provide satisfactory heating service using low temperature water from air source HPs. Radiant floor heating systems (RFHS) have become popular in residential, commercial and industrial spaces, because of their low energy consumption and comfortable service[2]. Since low temperature water from air source HP is able to meet the need of RFHS [3], the former is widely used as the heat source of the latter.

However, excessive operating cost is one of the main obstacles to the further promotion of AHPFHS. Therefore, it is important to find an optimal operation method of AHPFHS, which helps reduce the operating cost of the system. Several studies have been carried out on the economic dispatch for heating system. However, energy supply characteristics of the equipment and thermal characteristic of building have not been considered at the same time. The on/off state of air conditioning or output of energy supply equipment is often taken as optimization variable, but that is not suitable for AHPFHS， in which RFHS is often laid separately in each room, while the entire building is often equipped with one single HP, causing limitations in temperature settings. In this paper, a control strategy for the AHPFHS to meet the heat demand of different customers is proposed. A household AHPFHS was employed as a test system to illustrate the control strategy. The main contributions of this paper are summarized as follows:

1) The model of the household air source HP heating system is established based on the characteristics of the equipment; the residential building thermal load model is built based on the heat balance equation.

2) A rolling optimization control method is proposed. The indoor temperature set-point is scheduled to obtain the minimum operating cost of the AHPFHS considering the customer's thermal comfort.

3) A study case is built to validate the feasibility of the proposed method.

2. MODELING

The model in this paper is decomposed into two parts: an AHPFHS model and a building thermal load model.

2.1 Model of AHPFHS

The structure of an AHPFHS is shown in Fig 1. The system is composed of an air-source HP, a buffer tank, a low temperature hot water RFHS, and two circulating pumps (one for air-source HP and the other for heat network)[4].

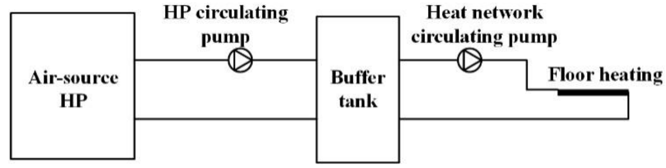

Fig 1 AHPFHS connection diagram

2.1.1 Air source HP

The power of the compressor is shown in Eq.(1) when the air-source HP is on.

$$P_{comp} = \frac{Q_{hps}(T_{s1}, T_e)}{COP(T_{s1}, T_e)} \quad (1)$$

Air-source HP is operated by on/off control to regulate buffer tank temperature[5], as shown in Fig.2.

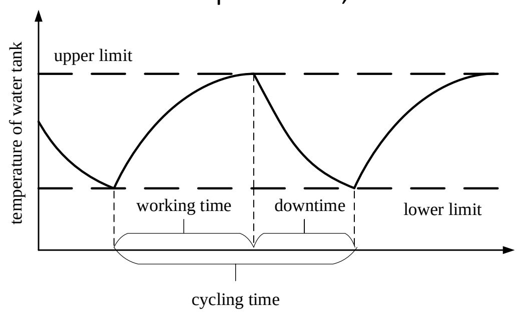

Fig 2 On/off control of air-source heat pump

The real-time power of AHPFHS is depicted as Eq.(2). The state parameters are depicted as Eq.(3) and Eq.(4).

$$P_t = (P_{vent} \cdot S_{fr} + P_{comp}) \cdot S_{hp} + P_{cp1}(q_1) + P_{cp2}(q_2) \quad (2)$$

$$S_{hp} = \begin{cases} 1, \text{when} \quad \text{HP is work} \\ 0, \text{when} \quad \text{HP is not work} \end{cases} \quad (3)$$

$$S_{fr} = \begin{cases} 1, \text{when not defrosting} \\ 0, \text{when defrosting} \end{cases} \quad (4)$$

2.1.2 Water at air-source HP outlet

The specific model of water at air-source HP outlet can be found in [4].

2.1.3 Buffer tank

In this paper, the multi-node approach[6] is utilized to describe the thermal stratification in the buffer tank. The tank is modeled as 5 fully mixed volume segments(nodes). The specific model of buffer tank can be found in [4].

2.1.4 Water at RFHS inlet

The volume flow of water at the outlet of air-source HP is depicted as Eq. (5).

$$q_2 = \frac{(T_{set} + dT_{up} - T_z) \cdot q_{2max}}{dT_{up} + dT_{low}} \quad (5)$$

2.1.5 RFHS

The heat power of RFHS depends on the water temperature at RFHS inlet & outlet, indoor temperature, and the design of the system. The specific model of RFHS can be found in [4].

2.2 Model of thermal load of the building.

The thermal storage capacity of the building is important in describing the thermal performance of buildings. Based on this, the building was modeled as a virtual energy storage system (VESS).

The mathematical relationship among indoor temperature, heating/cooling demand (equals to the heating/cooling power generated by the corresponding equipment) and ambient temperature is established using the thermal equilibrium equation of the building, as shown in Eq. (6). The meaning of the parameters can be found in [7]

$$k_{wall} \times F_{wall} \times (T_e - T_z) + k_{win} \times F_{win} \times (T_e - T_z) + I \times F_{win} \times SC + Q_{in} - c_w \cdot \rho_w \cdot q_2 \cdot (T_{s2} - T_{r2}) = c_a \cdot \rho_a \cdot V_z \cdot dT_z / dt \quad (6)$$

3. ROLLING OPTIMIZATION CONTROL STRATEGY

3.1 Control framework

It can be seen from equations (1)-(6) that the indoor temperature set-point T_{set} affects the power output of AHPFHS. Therefore, T_{set} is chosen as the control variable in this paper. Taking customers' behavior into account, the T_{set} is only controlled when customers are at home, and the AHPFHS is shutdown during the absence of the customer.

A conventional energy supply strategy for AHPFHS is that the desired indoor temperature (i.e., indoor temperature set-point) is a constant during home occupation, i.e. T_{set}=$T_{constant}$。

The whole control period is divided into uniform time windows, each time window is a control horizon, i.e. if t_k is the starting point of the *k*th control horizon, the indoor temperature set-point $T_{set,tk}$ at t_k is optimally adjusted according to the prediction result of the period t_k - t_{k+p} (i.e. the prediction horizon), and $T_{set,tk}$ remains unchanged in the control horizon. Taking the longtime scale of temperature into account, the control horizon is set to 15 minutes. Considering the prediction error and the trend of the prediction data, the prediction horizon is set to 24 hours.

The flow chart of the rolling optimization energy supply strategy based on T_{set} control is shown in Fig 3.

1) Obtain the indoor temperature at t_k through measuring devices of the building. Obtain the predicted 24-hour ambient temperature and light intensity from the weather station. Data mentioned above are input of the model of the building. Water tank temperature measured at t_k is utilized as the initial data for the AHPFHS.

2) Solve the optimization problem in the prediction horizon, and then determine the indoor temperature set-point at t_k. The indoor temperature set-point in t_k-t_{k+1} period is denoted by $T_{set,tk}$. When solving the optimization problem, the indoor temperature set-point in the prediction horizon is shown in Eq. (7). In the control horizon, the alternative indoor temperature set-point $T_{set,control}$ is determined through enumeration method in the range of acceptable temperature of human, [$T_{z,min}$, $T_{z,max}$], with the step size set to dT_z.

3) Set the indoor temperature of period t_k-t_{k+1} to $T_{set,tk}$.

By repeating step 1) to 3), thus the indoor temperature set-point optimization result at t_{k+1} is obtained. By continuously scrolling along the time axis, the set of indoor temperature set-point, $\boldsymbol{T}_{set}$={$T_{set,tk}$, $T_{set,tk+1}$, $T_{set,tk+2}$, ...} is obtained.

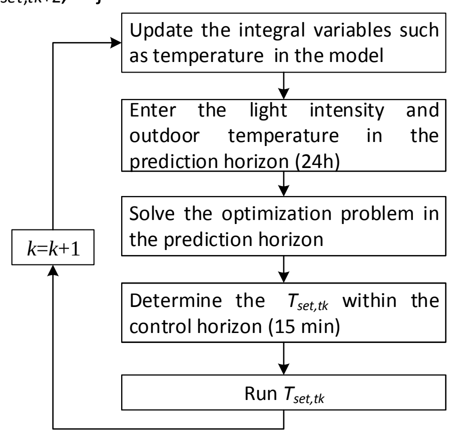

Fig 3 The flow chart of the rolling optimization energy supply strategy based on T_{set} control

$$T_{set} = \begin{cases} T_{set,control} & t \in [t_k, t_{k+1}) \\ T_{constant} & t \in [t_{k+1}, t_{k+p}] \end{cases} \quad (7)$$
$$T_{set,control} \in \{T_{z,min}, T_{z,min} + dT_z, T_{z,min} + 2 \cdot dT_z, \cdots, T_{z,max}\}$$

3.2 Objective function

The optimization model was built with the objective of minimizing the cost of AHPFHS in the prediction horizon. The objective function is shown in Eq. (8).

$$\min f(x,u) = \min \int_{t_k}^{t_{k+p}} C_{ec,t} \cdot P_t d\tau, \quad t \in [t_k, t_{k+p}]$$
$$\begin{cases} x = [P_{comp}, P_{cp1}, P_{cp2}, S_{fr}, S_{hp}] \\ u = T_{set} \end{cases} \quad (8)$$

Where $C_{ec,t}$ is spot price.

3.3 Constraints

Equality constraints include electric power balance constraint and heating demand balance constraint.

Inequality constraints include technical constraints such as the volume flow limitation and thermal comfort constraint.

In conditioned spaces, the thermal comfort conditions of can be evaluated by means of the predicted mean vote (PMV) index[8], which is: $T_{z,min} \le T_z \le T_{z,max}$. Where $T_{z,min}$ and $T_{z,max}$ are the limits defined by the particular class of ISO 7730 standard, in which the typical comfort range is between -0.5 and 0.5[9].

4. CASE STUDY

4.1 Case description

An AHPFHS shown in Fig.1 was used to illustrate the control results under the optimization objective. A typical winter day in the north is taken as an example, the ambient temperature and light intensity predicted by the weather station are shown in Fig 4 and Fig 5, respectively. The time-of-use power price is shown in Fig 6, according to the policy of Shanxi Province, China. The unoccupied hours are set to be from 8:00a.m. to 18:00p.m. The parameters of main equipment are shown in Table 1.

Table.1 Some typical parameters of equipments

Equipment	Parameter	Value
Air source HP	Rated capacity of HP	10kW
Building	Comfortable temperature upper bound T_{zmax}	26.7℃
	Comfortable temperature lowwer bound T_{zmin}	23.3℃
	Step size of indoor temperature set-point dT_z	0.2℃
	The most comfortable temperature T_n	25℃
	The initial indoor temperature	25℃
	The total thermal resistance of the roof	2.30(m^2*K)/W
	The total thermal resistance of the wall	2.28(m^2*K)/W
	The total thermal resistance of the floor	1.02(m^2*K)/W

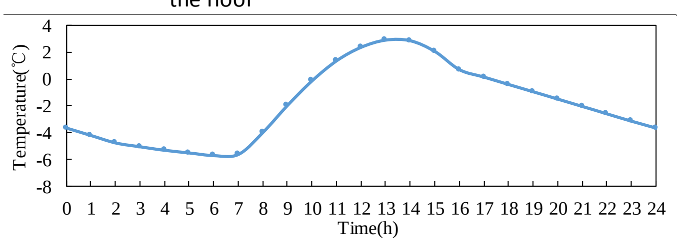

Fig 4 The ambient temperature

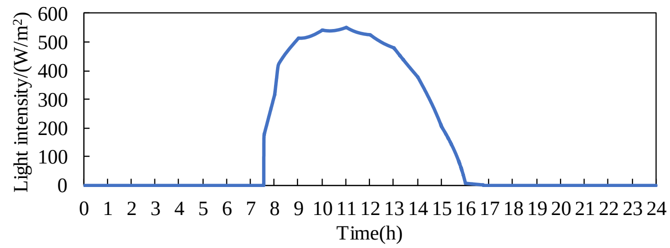

Fig 5 The light intensity

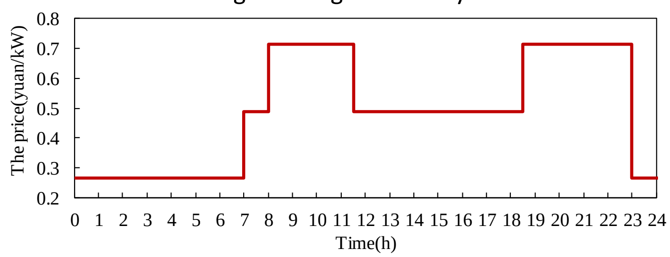

Fig 6 The time-of-use power price

4.2 Simulation Results

Scenario I: The conventional energy supply strategy: The indoor temperature is set to the most comfortable temperature, i.e. T_{set}=25℃.

Scenario II: The indoor temperature set-point T_{set} is optimally scheduled by rolling optimization control method proposed in this paper. The control horizon is 15 minutes, and the prediction horizon is 24 hours.

The system was simulated for 48 hours using the control strategy in scenario I. Since the customers are always at home in the 18-32 period, the analysis mainly focus on this section. The power consumed by AHPFHS in this period is shown in Fig 7. It can be seen in conjunction with Fig 8 that The working time in each cycle of the HP is increasing. The ambient temperature is decreasing at 18-31 period as shown in Fig 4.

The reason is: suppose that T_{set} stays as a constant, as the ambient temperature goes down, it is necessary to extend the working time of HP to meet the increasing heat demand. Meanwhile, the downtime of HP is shortened. Since the working time is much longer than the downtime, the former is dominant in a working cycle, thus the start-up frequency of HP decreases in 18-31 period as ambient temperature goes down.

The system was simulated for 48 hours using the control strategy in scenario II. The actual indoor temperature is shown in Fig 9. The indoor temperature in scenario II is always in the comfortable temperature range.

The electricity charge of the AHPFHS in 48 hours in the two scenarios is shown in Table 2. Compared with Scenario I, the 48-hour electricity charge of the AHPFHS in Scenario II is significantly reduced. It proves that the proposed method is able to reduce the operating cost of the AHPFHS effectively.

The electricity consumption of the AHPFHS in 48 hours in the two scenarios is shown in Table 3. Compared with Scenario I, the overall electricity consumption of the AHPFHS in Scenario II is reduced. The proportion of electricity consumption at a certain price period in two scenarios is shown in Table 4. Compared with Scenario I, the proportion of electricity consumption during peak time is increased in Scenario II, while the proportion during off-peak time or flat time is reduced. In summary, the rolling optimization control method proposed in this paper is able to influence the operating cost of the AHPFHS in two ways: on the one hand, electricity consumption of the AHPFHS is overall reduced. On the other hand, the proportion of electricity consumption during peak time is increased while that during off-peak time or flat time is reduced. The former is dominant, so the proposed method is able to reduce the operating cost of the AHPFHS.

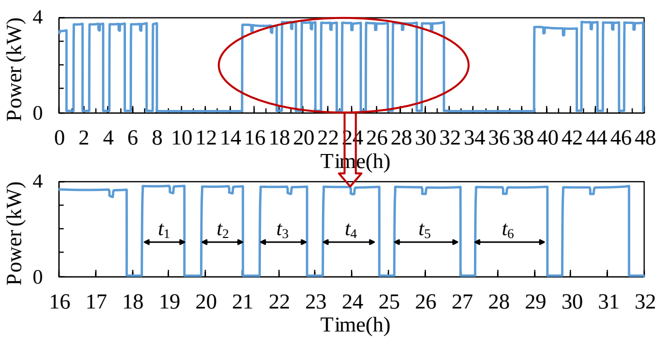

Fig 7 The power of the AHPFHS in 48 hours

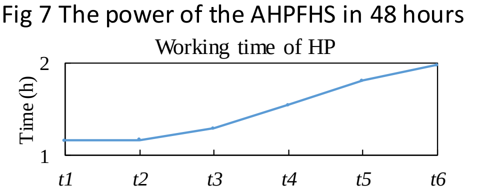

Fig 8 The working time in each cycle of the HP

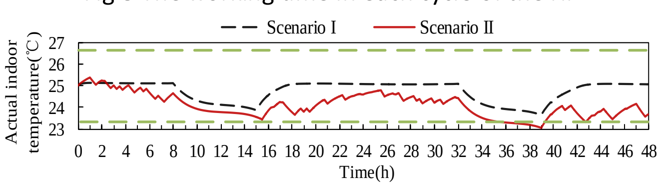

Fig 9 The actual indoor temperature in two scenarios

Table 2 The electricity charge in two scenarios

	Scenario I	**Scenario II**
Electricity charge (yuan)	43.67	37.71

Table 3 The electricity consumption in two scenarios

	Scenario I	**Scenario II**
Electricity (kWh)	98.00	84.00

Table 4 The proportion of electricity consumption at a certain price period in two scenarios

	Off-peak	**Flat**	**Peak**
Scenario I	45.88%	28.48%	25.64%
Scenario II	45.65%	25.77%	28.58%

5. CONCLUSION

The model of the household air source HP heating system is established based on the characteristics of the equipment; the residential building thermal load model is built based on the heat balance equation. A rolling optimization control method is proposed. The indoor temperature set-point is scheduled to obtain the minimum operating cost of the AHPFHS Considering the customer's thermal comfort. A study case was built to validate the feasibility of the proposed method.

Numerical studies show that under the conventional energy supply strategy, as the ambient temperature goes down, the start-up frequency of HP decreases, which is benefit to the facility. The proposed method is able to reduce the operating cost of the system effectively.

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