Study fuzzy variable supplied water temperature control for air-to-water heat pumps connected to a residential floor heating system

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Abstract. Reasonable supplied water temperature of air-to-water heat pump connected to the floor heating system can save energy and improve comfort. Based on the variation of hourly ambient temperature and ambient temperature, the fuzzy control table is established to adjust the supplied water temperature of the air-to-water heat pump. Considering the energy consumption and unsatisfied time in the whole season, the fuzzy control table is optimized by Hooke-Jeeves algorithm by a 100 m² building in Beijing. Comparing the conventional 45 ºC supplied water temperature, the simulation results show that the system energy consumption saved by 11.3% and unsatisfied time saved by 9.0% in the whole heating season.

1. Introduction

Floor heating system can accept lower temperature hot water and its popularity has been increasing over last years [1]. The combination of air-to-water heat pump and floor radiant heating can give full play to the advantages of air-to-water heat pump high efficiency and floor radiant heating comfort.

The supplied water temperature of the air-to-water heat pump has a great influence on the efficiency of the air-to-water heat pump. There are lots of researches have been conducted in order to improve the performance of the heating systems. Leiqh et al [2] study the relationship between the floor radiant heating system supplied water temperature and the outdoor temperature, and conclude that there is a linear relationship between the outdoor temperature and the required supplied water temperature of the floor radiant heating system. Karlsson et al [3] optimize the supplied fluid temperature by predicting the room heat demand for a single room, and the supplied fluid temperature is stable. Through EnergyPlus and BCVTB, Liu et al [4] establish the model of air-to-water heat pump connected to the floor radiant heating system for the 100 m² actual residential area in Shanghai, and save 40% energy by variable supplied water temperature control in the whole heating season. Jiang et al [5] obtain fitted curve between supplied water temperature and outdoor temperature through TRNSYS based on the outdoor temperature setting control regulation model under the premise of ensuring room temperature. The heating season save energy by 16.7%.

For multi-room buildings, reasonable optimization of the supplied water temperature is the key to the control of the heating system. Co-operative control of the floor heating system and the building, this paper proposes to make a fuzzy control table by the rate of hourly change of outdoor temperature and hourly outdoor temperature to control the supplied water temperature of the air-to-water heat pump. The stability of room temperature is represented by counting the time when the room
temperature doesn’t meet the setting temperature of the room. Aiming at reducing energy consumption and room unsatisfied time, this paper optimizes the control table through Hooke-Jeeves algorithm to control the supplied water temperature of the air-to-water heat pump.

2. Fuzzy variable supplied water temperature control method
The heating efficiency of the air-to-water heat pump and building heat load are obviously affected by the outdoor ambient temperature. With the change of outdoor temperature, the heat pump operates at the lowest supplied water temperature to meet the change of room heat demand, which is the key to energy saving and comfort. The paper uses MATLAB software to develop a fuzzy control table to control the variable supplied water temperature of the air-to-water heat pump by taking the difference the ambient temperature during the heating season, the difference between the current ambient temperature and the ambient temperature at the previous hour as the variables.

3. Heating system model
This paper builds a model of air-to-water heat pump connected to floor radiant heating system through TRNSYS (see Figure 1). The typical weather year climate database provides statistical climatic conditions for TRNSYS simulation [6].

The performance parameters of the heat pump and the unit test data provided by McQuay. The COP (heating coefficient of performance) of the air-to-water heat pump attenuation value $\text{COP}_{ht}$ caused by unit defrosting from the literature [7]. The actual power consumption of the air-to-water heat pump and water pump are calculated as follows:

$$P_m = \frac{\text{CAP}_r \times \text{CAP}_t}{\text{COP}_r \times \text{CAP}_t (1 - \text{COP}_{ht})} \tag{1}$$
$$Q_r = m \times \rho_i (t_t - t_i) \tag{2}$$
$$P_{wp} = \frac{Q_r}{\text{CAP}_r \times \text{CAP}_t} \tag{3}$$
$$P_{awhp} = P_m \times F_{wp} \tag{4}$$
Where, $\text{CAP}_c$ is heating capacity in the nominal operating condition, $\text{COP}_c$ is COP in the nominal operating condition, $\text{CAP}_r$ is the ratio of the performance curve heating capacity to $\text{CAP}_c$, $\text{COP}_r$ is the ratio of the performance curve COP to $\text{COP}_c$, $P_m$ is full load power consumption, $P_{awhp}$ is actual power consumption of the air-to-water heat pump, $Q_x$ is actual heating capacity, $P_{1r}$ is partial load rate, $t_g$ is the heat pump outlet temperature, $t_i$ is the heat pump inlet temperature, $C_p$ is the specific heat capacity, $P_{\text{pump}}$ is pump power, $H$ is pump head, $V$ is flow of water flowing through the pump every hour, $\eta$ is total pump efficiency, $\eta_p$ is pump motor efficiency, $\eta_m$ is pump shaft efficiency, $P_s$ is pump shaft power.

### 4. Fuzzy variable supplied water temperature control example

The building locates in Beijing and the building model uses a type 56 module to simulate a single-storey rural house with a building area of 100 m$^2$ and a height of 3.2 m. The detail information of the building is shown as [8]. The air-to-water heat pump is carried out by considering the MACO50ER5-AE. Detail parameters are shown in Table 1.

| Table 1. Equipment detail parameters. |
|--------------------------------------|
| **Quantity** | **Rated heating capacity (kW)** | **Rated power (kW)** |
| Air-to-water heat pump | 1 | 14.8 | 4.4 |
| Pump | 1 | 0.37 |

The two-position controllers are used to control the room temperature between 18 °C and 19 °C. The temperature of the outdoor environment is detected by the temperature sensor. The fuzzy control table is developed on MATLAB software by the variables of the difference between current ambient temperature and the difference between the current ambient temperature and the ambient temperature of the previous hour. The method of fuzzy control defuzzification uses the centroid method. The membership function in fuzzy control is trapmf type. Four variables ($f_1$, $f_2$, $f_3$, and $f_4$) are defined in the fuzzy control table. The fuzzy control output table is shown in Table 2.

| Table 2. Fuzzy control output table. |
|-------------------------------------|
| $t_o(a-h)-t_d(a)$ | ($-\infty$, $f_1$) | ($f_1$, $f_2$) | ($f_2$, $f_3$) | ($f_3$, $f_4$) | ($f_4$, $\infty$) |
| $t_o(a)$ | 0.8 | 0.85 | 0.9 | 0.95 | 1 |

Output fuzzy control calculation results from MATLAB software to the TRNSYS software. The relationship between the output of the fuzzy control output table and the setting supplied water temperature of the air-to-water heat pump equation as

$$L_{set} = L_{down} + (L_{up} - L_{down}) \cdot m_c$$  

(8)
Where, $t_{set}$ is air-to-water heat pump supplied water temperature setting, $t_{up}$ is air-to-water heat pump upper limit of supplied water temperature setting, $t_{down}$ is air-to-water heat pump lower limit of supplied water temperature setting, $m_c$ is fuzzy control output.

The limit supplied water temperature $t_{up}$ and $t_{down}$ are set to 45 °C and 25 °C. In order to improve the control precision, the domain of fuzzy control is optimized. In the optimization process, the coupling constraints of $f_1$, $f_2$, $f_3$, and $f_4$ can be considered. The Hooke-Jeeves algorithm on GenOpt software is used to optimize the parameters for greatly simplifying the optimization process.

The $f_1$, $f_2$, $f_3$, and $f_4$ are continuous change within the optimization range, and the optimization ranges are $[0.5, 4]$, $[0.1, 2]$, $[2, 10]$, and $[0.5, 6.5]$. The initial values are 2, 1, 6, and 3. The step values are 0.1. The optimization goal is the minimum cumulative power consumption and unsatisfied time during the heating season. The objective function $M_t$ as follows:

$$M_e = \frac{\sum H (P_{pump} + P_{awhp})}{\sum (P_{pump, 45} + P_{awhp, 45})}$$  \hspace{1cm} (9)

$$M_u = \frac{\sum H (h_{west} + h_{liv} + h_{bed} + h_{din})}{\sum (h_{west, 45} + h_{liv, 45} + h_{bed, 45} + h_{din, 45})}$$  \hspace{1cm} (10)

$$M_t = M_e + M_u$$  \hspace{1cm} (11)

Where, $M_e$ is energy consumption accumulation ratio, $M_u$ is unsatisfied time accumulation ratio, $H$ is total hours of heating season, $P_{pump, 45}$ is pump power under constant supplied water temperature of 45 °C, $P_{awhp, 45}$ is air-to-water heat pump power under constant supplied water temperature of 45 °C, $h_{west, 45}$ is room temperature of west bedroom below 18 °C or above 19 °C under constant supplied water temperature of 45 °C, $h_{liv, 45}$ is room temperature of living room below 18 °C or above 19 °C under constant supplied water temperature of 45 °C, $h_{bed, 45}$ is room temperature of bedroom below 18 °C or above 19 °C under constant supplied water temperature of 45 °C, $h_{din, 45}$ is room temperature of dining room below 18 °C or above 19 °C under constant supplied water temperature of 45 °C.

The optimized $f_1$, $f_2$, $f_3$, and $f_4$ are 2, 1.5, 6.3, and 2.9.

**Figure 2.** Hourly ambient temperature and hourly ambient temperature change.
As shown in Figure 2, the abscissa is the heating season time. The left ordinate is the hourly ambient temperature, and the right ordinate is the hourly ambient temperature change. The 40.9% hourly ambient temperature is [-2.9, 2.9] and 84.8% hourly ambient temperature change is [-1.5, 1.5].

The temperature fluctuation of each room in the fuzzy control heat pump supplied water temperature is shown in Figure 3-6.

As shown in Figure 3-6, the abscissa is the heating season time, from November 15 to March 15 of the following year, totaling 2,904 hours. The left ordinate is the room temperature of the west bedroom, living room, bedroom, dining room and the supplied water temperature setting of the heat pump. The right ordinate is the outdoor ambient temperature. The room temperature of all rooms can be basically guaranteed at room setting temperature range in the whole heating season. Among the four rooms, the unsatisfied time of the bedroom is the smallest, the unsatisfied time of the dining room is the largest, and the room temperature stability of the bedroom is higher than that of the dining room. The all room temperatures are fluctuated by the change of the outdoor ambient temperature and the setting supplied water temperature of the heat pump. The system power consumption under the different control supplied water temperature as shown in Table 3.

![Figure 3. West bedroom temperature under fuzzy control supplied water temperature.](image3)

![Figure 4. Living room temperature under fuzzy control supplied water temperature.](image4)
Figure 5. Bedroom temperature under fuzzy control supplied water temperature.

Figure 6. Dining room temperature under fuzzy control supplied water temperature.

Table 3. System power consumption under the different control supplied water temperature.

|                        | Constant control | Fuzzy control |
|------------------------|------------------|--------------|
| Power consumption (kWh)| 5037             | 4468         |
| Unsatisfied time (h)   | 3119             | 2838         |
| System average COP     | 2.34             | 2.63         |

The supplied water temperature under the fuzzy control can be saved energy by 11.3% and decreased unsatisfied time by 9.0% compared with the constant supplied water temperature of 45 °C. The heating system can increase the system average COP by 12.4%. The fuzzy control is used to adjust the supplied water temperature of the air-to-water heat pump to meet the room temperature, which greatly reduces the unsatisfied time of the room, and the power consumption of the heating system is also reduced.

5. Conclusions
Based the outdoor ambient temperature and the outdoor ambient temperature change, the fuzzy control table is optimized by Hooke-Jeeves algorithm to control supplied water temperature of the air-to-water
heat pumps connected to a residential floor heating system. The simulation results show that compared with the control strategy of constant supplied water temperature of 45 °C, the fuzzy control variable supplied water temperature can save energy by 11.3% in the heating season, improve system average COP by 12.4% in the heating season, and decrease unsatisfied time by 9.0% in the heating season. The control strategy of fuzzy control of supplied water temperature is adopted, which is remarkable in energy saving and is stable of room temperature.

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