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An optimal control strategy for built environment based on the human thermal sensation

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Abstract. The automatic control strategy of existing heating, ventilation, and air-conditioning (HVAC) systems generally determine the set-point of building thermal environment in accordance with the relevant design criterion or occupants' preference, and have not taken the real-time thermal sensation of human body into consideration, which may make the human body feel uncomfortable under the range of comfortable design parameters. In order to improve the thermal comfort of human body, this paper presented an optimal strategy for indoor building environment control based on the human thermal sensation. The control logic of indoor air temperature based on the thermal sensation of human body was given, and the linear adjustment algorithm was used for realizing the optimal adjustment of indoor temperature set-point. In order to evaluate the performance of the proposed control strategy, a numerical simulation platform was constructed, and a series of simulations were carried out to compare the set-point based and proposed control strategies. The results revealed that the proposed control strategy can improve human thermal comfort and have the potential in energy saving compared to the set-point based control strategy. The proposed control strategy is of significance for the application of current thermal comfort research results and the development of built environment automatic control theory.

1. Introduction

The building thermal environment is not only related to the comfort and health of human, but also related to the energy consumption and pollutant emission of buildings. The automatic control of building thermal environment should be on the premise of satisfying human thermal comfort, and then realize the safe and energy-saving operation of building equipment. The most widely control method of building thermal environment is based on the indoor temperature set-point, which commonly determined the set-point in accordance with the relevant design criterion or occupants' preference. However, the temperature set-point based control is hardly to satisfy the personal human comfort and can result in over-cooled and over-heated thermal environment. In order to solve the problem that the temperature set-point based control has not taken the human thermal sensation into consideration, many researchers [1,2] attempted to introduce the thermal comfort model (such as Predicted Mean Vote) into the building automatic systems. However, these models failed to reflect real-time thermal sensation into the automatic control logic of the building thermal environment. Moreover, several researchers [3,4] studied satisfaction based control strategy to solve the problem that the temperature set-point is difficult to determine and improve the personal thermal comfort. The results of these studies revealed that the satisfaction based control can achieve higher thermal comfort and more stable building thermal environment than set-point based control. However, the satisfaction-based control required the users to input their thermal sensation by Human Machine Interface (HMI), which may interrupt their normal work and lead to unstable control effect when the users forgot to input their real-time thermal sensation.

With the rapid development of artificial intelligence technology, the wristband devices that can real-time monitor human physiological characteristics, such as heart rate and skin temperature of the wrist, have become increasingly popular. Many researchers [5-7] have demonstrated the feasibility of using the physiological characteristics for estimating human thermal sensation. In order to decrease the limitation of satisfaction-based control, this study presents an optimal control strategy for indoor building environment control based on the human thermal sensation. Firstly, the control logic of indoor air temperature based on the thermal sensation of human body is given. Then, a linear adjustment algorithm is developed for realizing the optimal adjustment of indoor temperature set-point. Finally, a series of simulations are done in a numerical simulation platform to evaluate the performance of the proposed control strategy.

2. Optimized control logic and linear adjustment algorithm

The traditional control logic of indoor air temperature generally uses the set-point based control, which keeps the air temperature within the range of set-point by measuring the deviation between the indoor temperature and set-point temperature and outputting the control signal to the actuator. The schematic diagram of indoor air temperature control loop is shown in Figure 1. However, it is difficult to determine the indoor temperature set-point on the process of actual operation and the control method cannot reflect the thermal comfort of the users in real time.

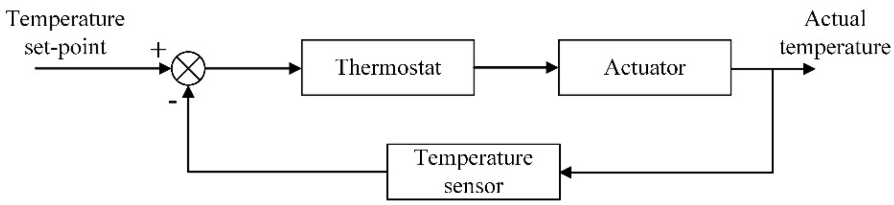

Figure 1. Schematic diagram of indoor air temperature control loop

Figure 2 shows the schematic diagram of indoor air temperature control loop with the thermal sensation. In the optimized control logic, the real-time thermal sensation of users have been introduced in the control logic. The optimized set-point is determined by the temperature set-point and thermal sensation at the current time.

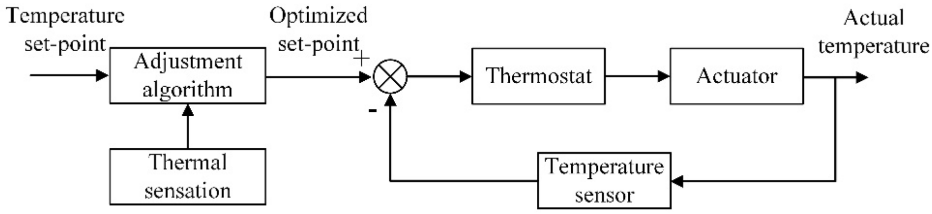

Figure 2. Schematic diagram of indoor air temperature control loop with the thermal sensation

In order to optimize the temperature set-point, a linear adjustment algorithm based on the human thermal sensation was proposed, which can be expressed as:

$$T_{\mathrm{STO}} = \begin{cases} T_{\mathrm{STMAX}} & TS < -2.5 \\ T_{\mathrm{ST}} + K_{\mathrm{TI}} \times (TS + 0.5) & TS \in [-2.5, -0.5) \\ T_{\mathrm{ST}} & TS \in [-0.5, 0.5) \\ T_{\mathrm{ST}} + K_{\mathrm{TD}} (TS - 0.5) & TS \in [0.5, 2.5] \\ T_{\mathrm{STMIN}} & TS > 2.5 \end{cases} \quad (1)$$

where T_{STO} is the optimized temperature set-point, T_{ST} is the un-optimized temperature set-point, TS is the human thermal sensation, T_{STMAX} is the upper limit of temperature set-point, T_{STMIN} is the lower limit of temperature set-point, K_{TI} is the linear adjustment constant corresponding to the increase of temperature set-point, K_{TD} is the linear adjustment constant corresponding to the decrease of temperature set-point.

In the linear adjustment algorithm, K_{TI} can be determined by the un-optimized temperature set-point and the upper limit of temperature set-point, which can be expressed by

$$K_{\mathrm{TI}} = \frac{T_{\mathrm{STMAX}} - T_{\mathrm{ST}}}{-2} \quad (2)$$

K_{TD} can be determined by the un-optimized temperature set-point and the lower limit of temperature set-point, which can be expressed by

$$K_{\mathrm{TD}} = \frac{T_{\mathrm{ST}} - T_{\mathrm{STMIN}}}{-2} \quad (3)$$

3. Simulation platform and process

In this study, the TRNSYS 17 simulation software was used to construct the simulation platform. The detailed information of the building were input by TRNBuild and the HVAC system was modeled by Simulation Studio. The simulation zone was an office room with the size of 13.2m×3m×4.2m (L×W×H), which was located in Dalian, China. The air-conditioning system was single duct variable air volume (VAV) system, which was operated from 8:00 to 18:00 every day. The zone was occupied by 4 people who was seated and performed slight work. The equipment load and light load was estimated in accordance with the area of the zone. The basic information of the zone are listed in Table 1.

Table 1. Basic information of the zone for simulation

Lists	Information	
Zone	Location	Dalian, China
	Use	Office room
	Size	13.2m×3m×4.2m (L×W×H)
AC System	Type	Single duct VAV system
Operating conditions	Schedule	8:00-18:00, 7 days working
	Supply air temperature	16℃
Load conditions	Occupant	Seated, Light work, typing: 150 W/person
	Equipment	16 W/m^2
	Light	13 W/m^2

In order to evaluate the performance of the proposed control strategy, four different settings have been simulated in this study. The time schedule of simulation process of the proposed control strategy is shown in Figure 3. Setting 1 and setting 2 represented two relatively extreme thermal sensation changes. In setting 1, the change sequence of thermal sensation was cold, warm, slightly cool, and neutral. On the contrary, the change sequence of thermal sensation in setting 2 was hot, cool, slightly warm, and neutral. Setting 3 and setting 4 represented two relatively mild thermal sensation changes. The change sequence of thermal sensation in setting 3 was cool, neutral, warm, and neutral. Meanwhile, the change sequence of thermal sensation in setting 4 was warm, neutral, cool, and neutral. The initial indoor temperature set-point was 25℃ in all four settings. Furthermore, several simulations that using set-point based control strategy were also conducted.

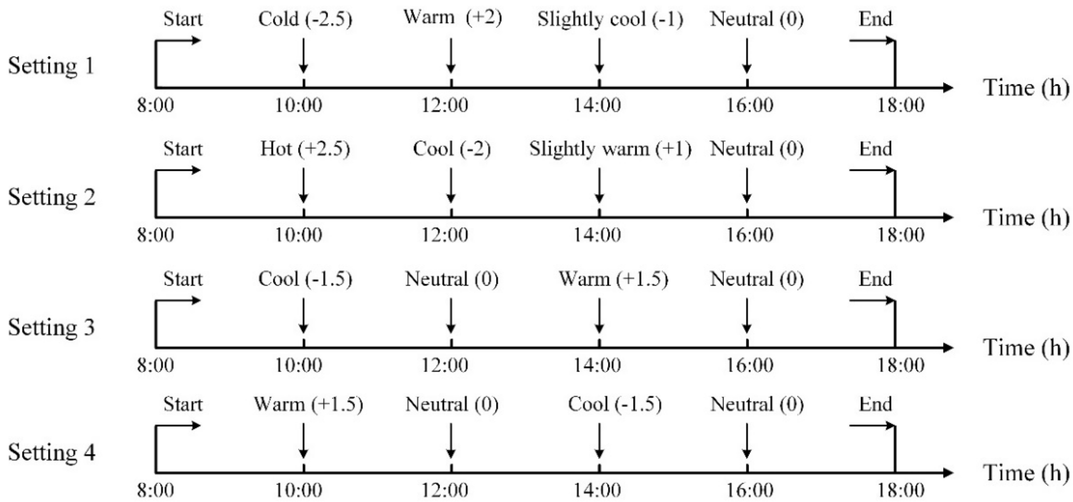

Figure 3. Time schedule of simulation process of the proposed control strategy

4. Results and discussion

Figure 4 shows the changes in indoor air temperature and outdoor temperature in setting 1, 2, 3, and 4. In all four settings, the outdoor temperature are the same and the indoor temperature set-point before 10:00 is 25℃. The optimized set-point has change when the thermal sensation input to the control loop.

The variation range of optimized set-point in four settings are 23.5-28℃, 22-26.5℃, 24.25-26.5℃ and 23.5-25.75℃, respectively.

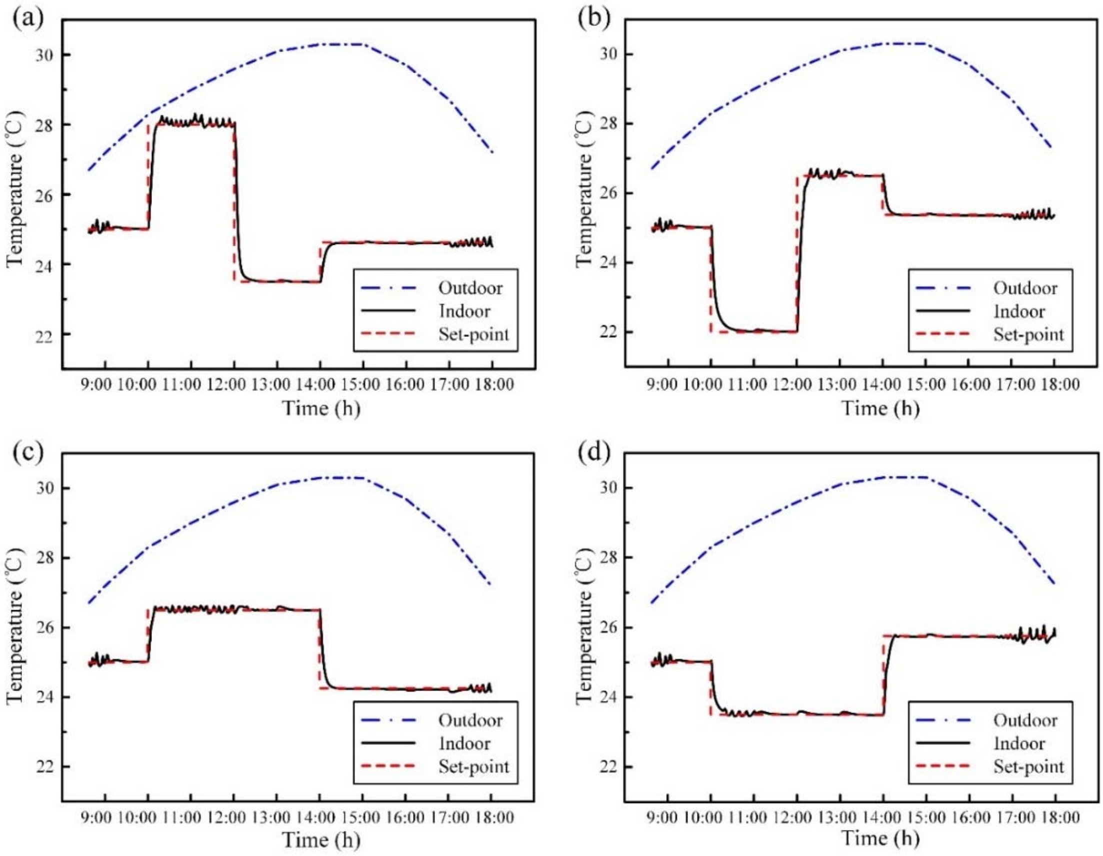

Figure 4. Indoor air temperature and outdoor temperature in four different settings control strategy of test day: (a) setting 1; (b) setting 2; (c) setting 3; (b) setting 4.

In order to evaluate the performance of the proposed control strategy, the overall energy consumption and predicted percentage of dissatisfied (PPD) have been calculated. The overall energy consumption included the fan consumption and cooling consumption. The predicted percentage of dissatisfied is an index that represents the percentage of thermally dissatisfied with the indoor thermal environment [8]. The smaller the value of PPD, the better thermal environment is realized. The computational formula of PPD is shown in equation (4).

$$\mathrm{PPD} = 100 - 95\exp[-0.03353\mathrm{PMV}^4 - 0.2179\mathrm{PMV}^2] \quad (4)$$

Figure 5 shows the average PPD of the set-point based and proposed control strategies. The PPD of the indoor temperature set-point in 24℃, 25℃, 26℃ were 16.8%, 17.9% and 20.26%, respectively. In the four settings of proposed control strategy, the average PPD of setting 2 and setting 4 were obviously below setting 1 and setting 3. Due to the initial indoor temperature set-point in the four settings was 25℃, we have made some comparisons of the average PPD between the indoor temperature set-point of 25℃ and proposed control strategies. The PPD of setting 2 and setting 4 were 7.9% and 19.9% lower than that of the indoor temperature set-point of 25℃. Meanwhile, the PPD of setting 1 and setting 3 were 1.2% and 7.8% higher than that of the indoor temperature set-point of 25℃.

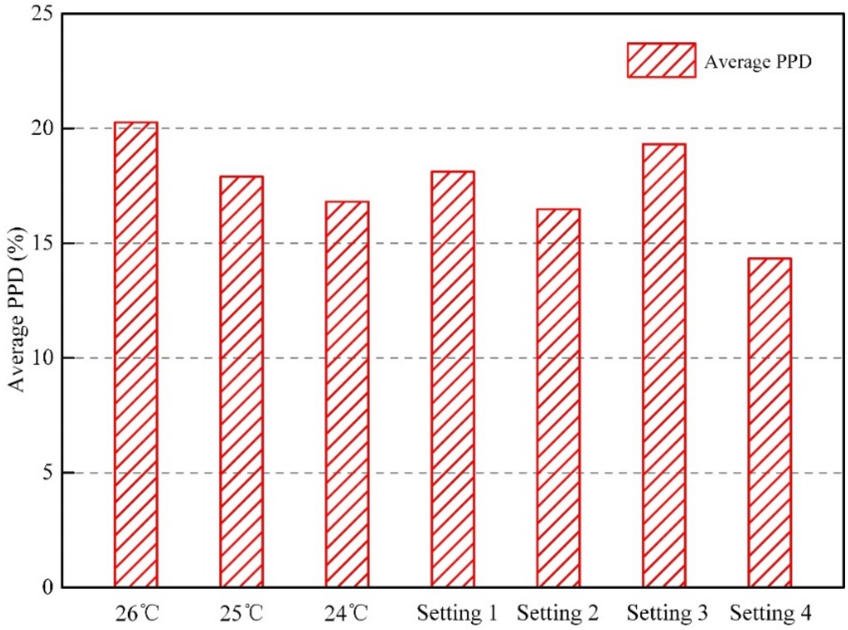

Figure 5. Comparison of the average PPD between two control strategies.

Figure 6 shows the overall energy consumption of the set-point based and proposed control strategies. The overall energy consumption of setting 1 was 2.39% lower than that of the indoor temperature set-point of 25℃. The overall energy consumption of setting 2, setting 3 and setting 4 were 3.74%, 1.02% and 4.52% higher than that of the indoor temperature set-point of 25℃. When considering both PPD and energy consumption, the setting 1 has saved energy with the decrease of thermal comfort while the setting 3 not only increased energy consumption but also reduced thermal comfort. The setting 2 and setting 4 improved thermal comfort with the cost of increasing energy consumption. Especially in setting 4, the PPD decreased 19.9% with the energy consumption only increased 4.52%. The results revealed that the proposed control strategy has the potential of improving thermal comfort with the cost of increasing a small amount of energy consumption.

The above results are obtained by comparing the proposed control strategy of different settings with the set-point based control strategy in 25℃. However, the indoor temperature set-point of the actual control system always lower than 25℃, which means that the proposed control strategy has greater potential in energy saving. In this study, the setting 2 and setting 4 not only improved thermal comfort but also decreased energy consumption compared with the set-point in 24℃. Therefore, we can come to the conclusion that the control strategy based on human thermal sensation can provide a more comfortable built environment and have the potential in energy saving.

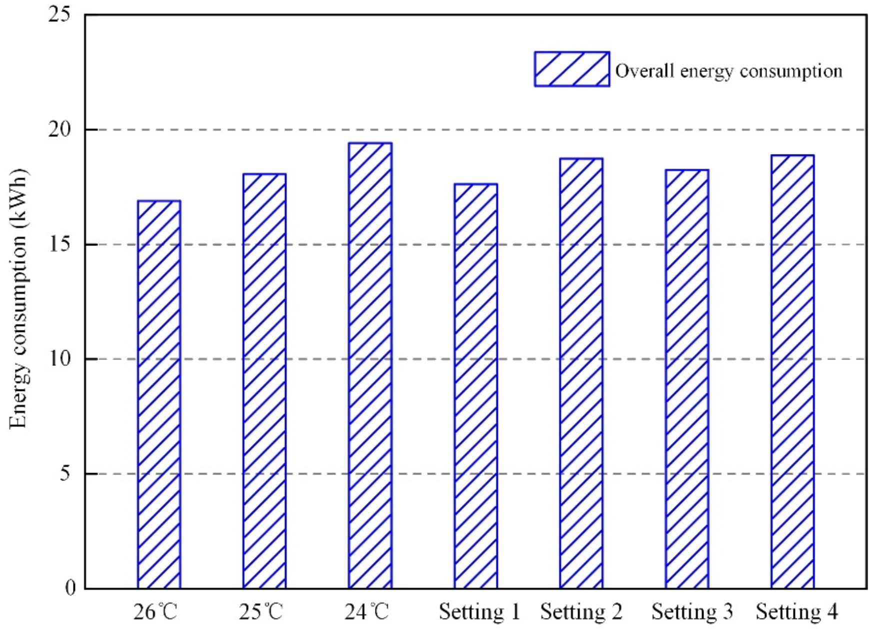

Figure 6. Comparison of the overall energy consumption between two strategies.

This study introduced the real-time thermal sensation of users into the control logic of indoor thermal environment, which was built on the basis of current thermal comfort research results. Moreover, a linear adjustment algorithm for realizing the optimal adjustment of indoor temperature set-point is proposed, which developed the automatic control theory of built environment. Even though the research results are significant, there are still some limitations in this study. First, only four settings of the proposed strategy have been considered in this study, which cannot cover all the thermal sensation changing situation. Moreover, the comparisons of the PPD and overall energy consumption between set-point based and proposed control strategies were based on the simulation results, which may be different from the actual condition. Accordingly, further studies are required to evaluate the performance of the proposed control strategy by many field experiments.

5. Conclusion

In this paper, an optimal strategy for indoor building environment control based on the human thermal sensation is proposed. A numerical simulation platform is constructed and a series of simulations are conducted to compare the set-point based and proposed control strategies. The results of the simulations illustrate that the control strategy based on human thermal sensation can provide a more comfortable built environment and have the potential in energy saving. The proposed control method is of significance for the application of current thermal comfort research results and the development of built environment automatic control theory.

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