Simulation on the Indoor Thermal Environment Control Considering Discomfort Probability

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ABSTRACT

The reasonable indoor thermal environmental control should be able to well balance the tradeoff between comfort and energy consumption. However how to quantitatively evaluate the tradeoff between comfort and energy is a difficult issue and still lacks of adequate study. This paper proposes an on-line learning method to build the model of discomfort probability of a room occupant. Base on the discomfort probability model, this paper uses simulation to study the energy consumption and productivity changes at different discomfort probabilities for the purpose of quantitatively evaluating the tradeoff between comfort and energy consumption. For the case study rooms, simulation results show that if the discomfort probability increases from 0.05 to 0.10, the cooling energy consumption decreases by 16.4% and heating energy consumption decreases by 10.5%. Meanwhile the accompanying to the discomfort probability increase, the productivities of room occupants tend to decrease. The gross domestic production (GDP) is used as an index to evaluate the quantitative tradeoff between energy saving and productivity decrease. The simulation results show that for cooling case, when the discomfort probability is 0.0875, the synthetic GDP benefit of energy saving and productive decrease reaches maximum. Similarly, for the heating case, the optimal discomfort probability exists at 0.075.

KEYWORDS

Thermal comfort, Productivity, Energy consumption, Discomfort probability, Indoor environment control

INTRODUCTION

Current indoor thermal environment is usually controlled based on a temperature set-point given by room occupants or building managers. However, investigation shows that many temperature set-points are unreasonable, resulting in not only uncomfortable indoor thermal environment, but also waste of cooling or heating energy [1].

In the attempt to improve indoor environment control method, a satisfaction based control concept is studied. This control system collects users' thermal complaints of 'hot', 'cold', etc., and uses an online learning algorithm to acquire users' comfort regions and gives optimal set-points. Experiment and comparison study show that the satisfaction based control method can achieve satisfactory control performances and is more energy-efficient than the conventional set-point based control [2]. However, the comfort model used in the said satisfaction based control is a Classifier Model [3], which is completely data driven and doesn't take the tradeoff between comfort and energy consumption into consideration.

This paper proposes an on-line learning method to build the discomfort probability models of room

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occupants. Based on the discomfort model, this paper uses simulation to study the energy consumption and productivity changes at different discomfort probabilities for the purpose of quantitatively evaluating the tradeoff between comfort and energy consumption.

METHODOLOGY

Discomfort probability model

Wang proposes a mathematical model in his Ph.D. dissertation to describe the probability of building occupants' behaviors [4]. It is pointed out that when indoor environment parameters deviate from occupants' comfort regions, they tend to adjust the environment; and the larger the deviation is, the higher the probability of adjusting is. These rules apply to occupants' complaint behaviors as well. For instance, room occupants have more chance to complaint hot when the indoor temperature is higher. So that occupants' environment-related discomfort probability models can be built. As temperature is the most important indoor environment parameter [5], this paper focuses on the thermal (hot and cold) discomfort probability models.

The basic form of the discomfort probability model is shown in Equation (1), in which P is the discomfort probability; $\lambda(t)$ is a function related to indoor temperature t.

$$P = 1 - e^{-\lambda(t)} \tag{1}$$

Considering the psychological stimulation caused by the environment deviation, Steven's power law [6] (Equation (2)) is applied, in which S is a psychological quantity reflecting the stimulation level, t_0 is the stimulation threshold of indoor temperature, a and b are model coefficients.

$$S = a \cdot (t - t_0)^b \tag{2}$$

So that $\lambda(t)$ in a monotone increasing form can be transformed into Equation (3), in which L and k are coefficients to be determined.

$$\lambda(t) = \left(\frac{t - t_0}{L}\right)^k \qquad (t > t_0, L > 0, k > 0) \tag{3}$$

The hot and cold discomfort probability models are respectively shown in Equations (4) and (5). From the models, we can find it reasonable that when out of the comfort thresholds, P_{hot} and P_{cold} increases respectively with the increasing and decreasing of room temperature.

$$P_{\text{hot}} = \begin{cases} 1 - e^{-\left(\frac{t - t_{0,\text{hot}}}{L}\right)^k} & t > t_{0,\text{hot}} \\ 0 & t \le t_{0,\text{hot}} \end{cases} \tag{4}$$

$$P_{\text{cold}} = \begin{cases} 1 - e^{-\left(\frac{t_{0,\text{cold}} - t}{L}\right)^k} & t < t_{0,\text{cold}} \\ 0 & t \ge t_{0,\text{cold}} \end{cases} \tag{5}$$

In our previous study [2], 10 days' satisfaction based experiments under cooling and heating conditions were conducted respectively at two test-beds in Guangzhou and Lanzhou, China. Experiment data is used to build users' discomfort models. Temperature and complaint data are divided into intervals with the time step of $\Delta\tau$ =15min. Under the condition of room temperature T=t, a user's hot discomfort probability can be calculated as a conditional probability with Equation (6), which is the proportion of numbers of intervals where hot complaint occurs (C_{hot}=1) to numbers of all intervals with T=t.

$$P_{\text{hot}}(t) = P(C_{\text{hot}} = 1 \mid T = t) = \frac{N\{\tau_i : C_{\text{hot},\tau_i} = 1, T_{\tau_i} = t\}}{N\{\tau_i : C_{\text{hot},\tau_i} = 1, T_{\tau_i} = t\} + N\{\tau_i : C_{\text{hot},\tau_i} = 0, T_{\tau_i} = t\}} \tag{6}$$

After the discomfort probabilities under different temperature conditions are achieved, coefficients t_0, L and k in Equations (5) and (6) can be fitted and users' discomfort models can be built. For instance, in the cooling case, one typical user's hot and cold discomfort models are shown in Equations (7) and (8), and fitted model are shown in Figure 1.

$$P_{\text{hot}} = \begin{cases} 1 - e^{-\left(\frac{t-27.5}{69.327}\right)^{0.865}} & t > 27.5 \\ 0 & t \le 27.5 \end{cases} \tag{7}$$

$$P_{\text{cold}} = \begin{cases} 1 - e^{-\left(\frac{29.0-t}{3.205}\right)^{4.278}} & t < 29.0 \\ 0 & t \ge 29.0 \end{cases} \tag{8}$$

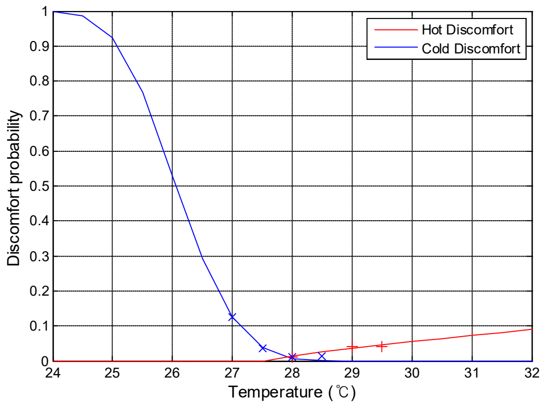

Figure 1. Typical user's discomfort probability models

Set-point algorithm

Using the discomfort model, the probability of a user's complaining hot or cold can be predicted with room temperature data. In other words, indoor temperature can be controlled to keep user's discomfort probability at a certain level.

To control indoor temperature, we can give a probability threshold, then use the discomfort models of occupant i to calculate the temperature threshold of his/her comfort region. For a group of occupants, the group comfort region can be determined as [max$(t_{c,i})_{\text{cold}}$, min$(t_{c,i})_{\text{hot}}$], where max$(t_{c,i})_{\text{cold}}$ represents the maximum temperature thresholds calculated by all users' cold discomfort models, and min$(t_{c,i})_{\text{hot}}$ represents the minimum temperature thresholds calculated by all users' hot discomfort models.

Indoor temperature set-point can be selected from the group comfort region. Considering energy saving, we can take the upper bound of the group comfort region for cooling set-point, and the lower bound for heating, as shown in Equation (9).

$$t_{\text{c,group,set}} = \begin{cases} \min(t_{\text{c},i})_{\text{hot}}, & \text{if cooling} \\ \max(t_{\text{c},i})_{\text{cold}}, & \text{if heating} \end{cases} \tag{9}$$

Simulation model

To verify the effect of temperature control based on discomfort probability, simulation study is conducted. Simulation model is built in MATLAB Simulink. The main structure of the model is shown in Figure 2. The Room module uses State Space Method [7] to simulate thermal dynamics and temperature change; the AC System module simulates the air conditioner output; the Controller module reads the temperature set-point uses PID algorithm to adjust air conditioner's duty ratio based on the difference between indoor temperature and the set-point; the Complaint module collects temperature data to calculate the discomfort probability with users' discomfort models and generates hot/cold complaints; the Model Update module uses temperature and complaint data to update occupants' discomfort models.

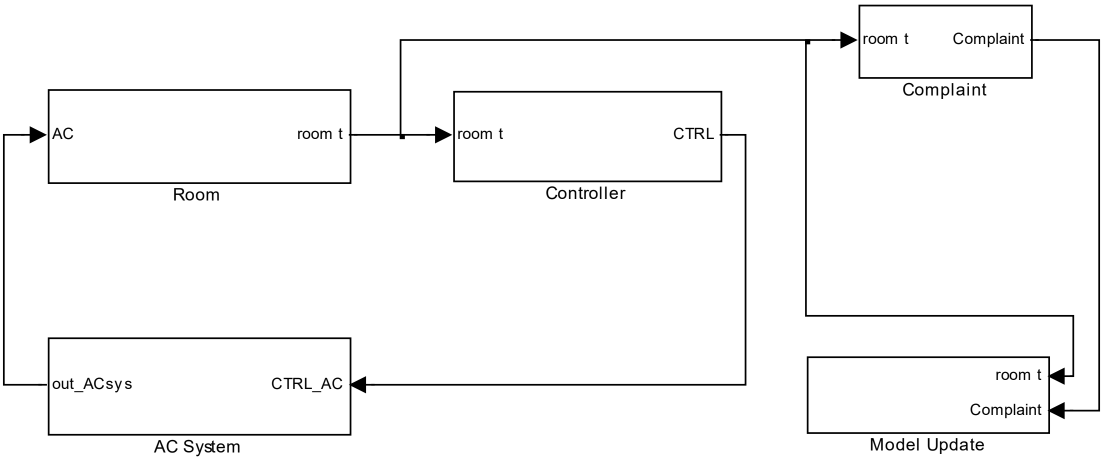

Figure 2. MATLAB Simulink model

In this study, cases with discomfort probability threshold from 0.05 to 0.10 are simulated. We use the 10 days' experiment data to build the initial discomfort models, and run 5 days' simulation for each case. With the simulation running, newly generated temperature and complaint data are recorded. After each day's simulation, discomfort models are updated using the latest 10 days' data and new set-point is achieved for the next day's simulation.

RESULTS AND DISCUSSION

Influence of different discomfort probability thresholds

According to the discomfort model form and the set-point algorithm proposed above, we can expect that the larger the discomfort probability threshold we give, the wider the comfort region will be, and the more energy-efficient temperature set-point can be determined, but more discomfort complaints may occur. From our simulation study, this trend is confirmed, as shown in Table 1. Data in each line are the average of 5 days' simulation for each probability threshold. From Table 1, we can find that temperature set-point shows a rising tendency with the discomfort probability increasing under the cooling condition, and drops under the heating condition. And with the discomfort probability increasing from 5% to 10%, air conditioner's cooling energy consumption decreases by 16.4% and heating energy consumption decreases by 10.5%, but the number of complaint doubles.

Table 1. Influence of different discomfort probability thresholds

Discomfort probability threshold	Cooling			Heating		
	Set-point / ºC	AC power / W	Complaints per capita	Set-point / ºC	AC power / W	Complaints per capita
0.05	29.32	1813	1.2	23.61	1729	1.1
0.0625	29.55	1736	1.4	23.46	1690	1.3
0.075	30.17	1580	1.5	22.92	1579	1.3
0.0875	30.43	1495	1.7	22.86	1576	2.5
0.10	30.42	1516	2.5	22.69	1548	2.6

GDP analysis

From the simulation data, tradeoff can be found between energy consumption and user comfort with the discomfort probability changing, and this paper attempts to find a quantitative way to evaluate this tradeoff. We use the gross domestic production (GDP) as an index to assess the economic benefit or loss. The main analysing approach is as followed:

1) Select a probability value as the benchmark of ‘comfort’. In this paper, we use 0.05 as the benchmark probability, i.e. set-point calculated by probability threshold 0.05 is considered comfortable for users.

2) Compare AC power consumptions between other discomfort probabilities and the benchmark, and calculate weekly energy savings under the assumption that users work 40 hours per week.

3) Convert the energy saving into equivalent of coal (ce). In China, the average consumption of cold-fired power generation is 305 gce/kWh.

4) Assume that the energy (coal) saving can be used for domestic production. The data of ‘Coal consumption per unit GDP’† can be used to estimate the GDP value created by the above energy saving, as shown in Equation (10):

$$\text{GDP}_\text{E} = \text{Coal saving / Coal consumption per unit GDP} \quad (10)$$

For the cooling case at Guangzhou test-bed, the value of ‘Coal consumption per unit GDP’ is about 0.05 tce/thousand RMB; for the heating case at Lanzhou test-bed, the value is 0.12 tce/thousand RMB.

5) Estimate users’ productivity decrease. For office users, thermal discomfort influences their productivity, which causes economic loss. In this paper, we apply a model describing the relationship between user productivity and room temperature [8] to estimate the productivity decrease *PD*, as shown in Equation (11):

$$PD = 1 - (0.1647524 \cdot t - 0.0058274 \cdot t^2 + 0.0000623 \cdot t^3 - 0.4685328) \quad (11)$$

$$t = t_c' + t_a - t_c \quad (12)$$

In Equation (12), room temperature t is converted with the comfort temperature in the reference literature t_c' and the simulated room and comfort temperature t_a and t_c in this study.

6) Estimate the GDP loss caused by productivity decrease using ‘Capita GDP’ and the *PD* value with Equation (13):

† ‘Coal consumption per unit GDP’ here and ‘Capita GDP’ below are the 2014 data published by the National Bureau of Statistics of China.

$$\mathrm{GDP_W} = PD \times \text{Capita GDP} \times \text{Occupant number} \tag{13}$$

For the cases in Guangzhou and Lanzhou, the annual Capita GDP values are respectively 63,469 and 26,433 RMB (which should be converted into weekly values). And for the two test-beds, the occupant numbers are respectively 10 and 15.

7) Calculate the GDP index to evaluate the tradeoff between energy saving and productivity loss:

$$\Delta\mathrm{GDP} = \mathrm{GDP_E} - \mathrm{GDP_W} \tag{14}$$

The larger $\Delta\mathrm{GDP}$ is, the more synthetic economic benefit we can get.

Calculating results of the simulated cases are listed in Table 2. For the cooling case, when the discomfort probability is 0.0875, the synthetic GDP benefit of energy saving and productive decrease reaches maximum. Similarly, for the heating case, the optimal discomfort probability exists at 0.075. From the simulation study, we can find that for an ordinary office room with occupancy of 10-15, it is more economically beneficial to give the temperature set-point with a slightly higher discomfort probability than the comfort level.

Table 2. GDP analysis results for simulated cases (weekly)

Case	Discomfort probability threshold	Temperature / ºC	Energy saving / kWh	Coal saving / kgce	$\mathrm{GDP_E}$ /RMB	Productivity decrease / %	$\mathrm{GDP_W}$ /RMB	ΔGDP /RMB
Cooling	0.05	29.32	-	-	-	-	-	0
	0.0625	29.55	3.07	0.94	18.73	0.01	12.79	5.94
	0.075	30.17	9.33	2.85	56.90	0.24	29.17	27.73
	0.0875	30.43	12.73	3.88	77.63	0.33	40.74	**36.89**
	0.10	30.42	11.87	3.62	72.40	0.33	40.28	32.13
Heating	0.05	23.61	-	-	-	-	-	0
	0.0625	23.46	1.56	0.48	3.96	0.09	6.65	-2.69
	0.075	22.92	6.02	1.84	15.30	0.15	11.57	**3.73**
	0.0875	22.86	6.12	1.87	15.56	0.17	12.64	2.92
	0.10	22.69	7.27	2.22	18.49	0.21	16.30	2.19

CONCLUSIONS

This paper proposes an indoor thermal environmental control method based on occupants' discomfort probabilities. Discomfort probability models are built and set-point algorithm is put forward. Simulation model is set up in MATLAB Simulink and case studies are conducted to verify the control effect. Meanwhile, a quantitative way using GDP index to evaluate the tradeoff between energy consumption and user comfort is proposed. For the simulation cases, the most economically beneficial discomfort probabilities are found. For the actual application of the this control method, building managers can use local economic data and follow the proposed approach to analyze the synthetic benefit, then determine the best discomfort probability and optimize indoor environment control.

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