Simulation of Indoor Thermal Environment Control Considering the Probability of Submitting Discomfort Sensations from Room Occupants with Different Temperament Types

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Abstract

Studies about temperament type in psychological field can be applied to indoor thermal environment control. Experiments on thermal discomfort complaint show that in the four typical temperament types, people having sanguine temperament are more likely to submit discomfort thermal complaints. A model for predicting the probability of submitting discomfort thermal complaints using skin temperature and considering people's sanguine temperament scores is developed for optimizing the thermal environment control. The performance of indoor thermal environment control based on discomfort thermal complaints probability is simulated with different temperament type in Matlab Simulink environment. Optimal thresholds of discomfort complaints probability are obtained for the people with different sanguine temperament scores by simulation. A simple linear equation between the optimal complaint thresholds and the scores of sanguine temperament is fitted, which is useful for field application to achieve optimal control of indoor thermal environment considering people's temperament with a simple rule.

Introduction

The present indoor thermal environment control commonly uses the temperature set points given by room occupants. However, field investigation (Wang et.al., 2014) shows that half of the temperature settings are out of the comfort range recommended by standards and design handbooks (ASHRAE, 2017), which causes not only uncomfortable overcooling/overheating thermal environment but also energy waste. To solve this problem, the authors proposed an alternative method that controls the thermal environment based on occupants' uncomfortable thermal sensation instead of temperature settings. The thermal sensations are input from an interface on a smart phone, computer, etc., when they feel thermally uncomfortable.

The probability of occupants submitting discomfort complaints is quite related to their temperament types. With the knowledge in the field of ergonomics, it can be supposed that the complaint frequency in indoor thermal environment differs depending on occupants' temperament type. According to the trait theory developed by Eysenck (1947), people's temperament can be divided into four types, which are named sanguine,

choleric, phlegmatic and melancholic. People with sanguine temperament are active, which can be defined as extroversion-stable neuroticism. Choleric people are more likely to get angry, which can be defined as extroversion-instable neuroticism. Phlegmatic people response slowly to the change outside, which can be defined as introversion-stable neuroticism. Melancholic people are more depressed than others and can be defined as introversion-instable neuroticism.

The goal of indoor thermal environment control should be to ensure the thermal conditions are comfortable enough that no discomfort complaint occurs. So the control method should be able to reduce the discomfort complaint as much as possible. However, because of the diversity of human beings' comfort range, for a multi-occupied room, there might not exist a commonly comfortable temperature. At this situation, the people with higher sanguine temperament tend to complain more times and the control system without considering temperament will tune the room temperature only according to the complainers. This is unfair to the people that complain less and the uncomfortable temperature might decrease their productivity. The purpose of this study is to find out the relationship between people's temperament and the behaviour of submitting thermal discomfort complaint. And on this basis, a model for predicting the probability of thermal discomfort complaint considering different temperament scores is developed. Based on the model, simulation is conducted to determine the optimal control parameter, which is the threshold of thermal discomfort complaint probability considering temperament type. The contents of this paper include the following parts: firstly, the model of predicting thermal discomfort complaint is explained; Then the experiments used to fit the parameters in the model are described; Finally the how the optimal control parameter is determined by simulation is described.

Modelling the probability of thermal complaint considering temperament type

Wang (2016) proposed a model for predicting the probability of a human behaviour of operating an indoor environment control device, as shown in Equation 1.

$$P = 1 - e^{-\varphi(x)\Delta\tau} \quad (1)$$

Where,

P – Probability of a human behavior

$\varphi(x)$ – The stimulation to trigger a behaviour. The x represents the stimulus, for example the temperature threshold to trigger a hot/cold complaint, the illumination to trigger turning on the lights, etc.

$\Delta\tau$ – Time of accumulating the stimulation

Based on this model, a model to predict the probability of submitting thermal discomfort complaint can be developed considering human being's psychological factor. The stimulation is the deviation of human skin temperature from the comfort range. This deviation has a psychological impact on users behaviour of submitting a thermal discomfort complaint. According to psychological research, the power law can be used to describe the impact of the deviation on human behaviour, as shown in Equation 2 (Kantowitz, et al., 2009).

$$S = a(I - I_0)^b \quad (2)$$

Where,

S - Psychological quantity reflecting the strength of the stimulus

I - Environment stimulus

I_0 - Threshold of the environment stimulus

a, b - Empirical coefficient

Thus, the probability model of thermal discomfort complaints of hot/cold with the change of the skin temperature is put forward as follows:

$$P_{cold} = \begin{cases} 0 & t_{skin} \geq t_{0,cold} \\ 1 - e^{-a(s)(t_{0,cold} - t_{skin})^{b(s)}} & t_{skin} < t_{0,cold} \end{cases}$$

$$P_{hot} = \begin{cases} 1 - e^{-a'(s)(t_{skin} - t_{0,cold})^{b'(s)}} & t_{skin} > t_{0,hot} \\ 0 & t_{skin} \leq t_{0,hot} \end{cases} \quad (3)$$

Where,

P_{cold} – Probability of cold complaint

P_{hot} – Probability of hot complaint

$t_{0,cold}$ - Skin temperature threshold of cold complaint (°C)

$t_{0,hot}$ - Skin temperature threshold of hot complaint (°C)

t_{skin} - Skin temperature (°C)

s - Score of expressing a user's temperament type (-)

The coefficients of a, b, a' and b' in the Equation 3 need to be determined according to users' individual characteristics. Experiments were conducted to collect data for fitting the coefficients of a, b, a' and b' . For the purpose of considering a user's individual characteristics, the values of the coefficients of a, b, a' and b' are the function of the user's temperament type s .

Experiments

In order to find the relationship between complaints and subjects' temperament, experiments were conducted before the simulation. In total 18 subjects were recruited and were divided into 6 groups. Each subject needs to complete 5 experimental units. Before the experiment started, all subjects were tested with a psychological questionnaire consisting of 60 questions to check their temperament types (Zhang and Chen, 1985).

Corresponding to each question, the subject gets score 2 for voting "very consistent", score 1 for voting "slightly consistent", 0 for "neutral", -1 for "slightly not consistent" and -2 for "not consistent". The results of each subjects' scores for the four parts of temperament type are as shown in Table 1.

Table 1: Scores of experiment subjects' temperament type

Subject No.	choleric	sanguine t	phlegmatic	Melan cholic
01	11	4	7	14
02	-2	11	7	-5
03	13	19	1	6
04	-2	-2	7	4
05	-1	-6	7	11
06	-4	6	4	0
07	-2	6	6	13
08	-1	1	7	10
09	-6	8	9	12
10	11	4	7	14
11	0	5	7	-1
12	-3	11	0	-15
13	1	-6	2	8
14	2	11	-4	-7
15	12	3	1	14
16	10	3	-10	0
17	-3	2	13	-3
18	3	9	1	-1

If the score of a certain part of temperament is obviously higher than the other three (difference ≥ 4), the subject tends to be this kind of temperament. If the scores of two or three parts of temperaments are similar (difference ≤ 3) and are obviously higher than the others (difference ≥ 4), then the subject tend to be the two-type-mixed temperament.

After obtaining the subjects' temperament scores, the experiment of control based on thermal sensation expression started. The experiment procedure is shown in Figure 1. After the test bed is ready, three subjects entered the experimental room, conducted their usual office or study activities, and complained when they felt cold or hot through the Human Machine Interface (HMI, Figure 2) on the smart phones. The duration of each experimental unit was 4 hours.

Figure 1: Procedure of the experiment of control based on thermal sensation expression

Figure 2: The HMI for subjects to express discomfort thermal sensations

Relations between complaint times and temperament type

The temperament test results and complaint times are shown in Table 2. In order to find out the relations between users' temperament type and thermal complaint times, the four temperaments scores are associated with the average complaint times per capita, as shown in Table 3.

From the Table 3, it can be found that subjects' thermal complaint behaviour is more closely related to the sanguine temperament. So the relations between the score of sanguine temperament and the complaint times is correlated, as shown in Figure 3.

From Figure 3, it can be learnt that people's thermal complaint behaviour is positively correlated with the score of sanguine temperament, which means that people more sanguineous tend to express their thermal complaints more.

It should be noted that Figure 3 is only used to show that the people with higher sanguine score tend to complain more times. The correlation formula shown in Figure 3 is just used to show the correlation level but is not used in the later analysis. The experimental data are used to fit the coefficients of a , b , a' and b' shown in Equation 3. The fitted coefficients for each experiment subject are shown in Table 4.

Table 2: Complaint times and temperament of experiment subjects

Subject No.	Complaint Times (daily average)	Temperament
01	1.50	0.56melancholic+0.44cholerich
02	8.13	1.00sanguine
03	2.25	1.00sanguine
04	3.63	0.64phlegmatic+0.36melancholic
05	2.00	1.00melancholic
06	1.75	0.60sanguine+0.40phlegmatic
07	0.00	1.00melancholic
08	0.60	0.59melancholic+0.41phlegmatic
09	0.80	0.41melancholic+0.31phlegmatic + 0.28 sanguine
10	1.00	0.56melancholic+0.44cholerich
11	0.00	0.58phlegmatic+0.42sanguine
12	0.00	1.00sanguine

13	1.50	1.00melancholic
14	1.17	1.00sanguine
15	1.17	0.54melancholic+0.46cholerich
16	5.29	1.00cholerich
17	1.43	1.00phlegmatic
18	1.14	1.00sanguine

Table 3: Daily average complaint times vs temperament of experiment subjects

Temperament	Complaint Times (Per capita)
sanguine temperament	6.95
cholerich temperament	4.96
phlegmatic temperament	4.38
melancholic temperament	3.92

Figure 3: Daily average complaint times vs the scores of sanguine temperament

Table 4: Value of Different Users' Coefficients

	User	a	b	t ₀ (°C)	R^2	Sanguine scores
Cold complaint	1	0.087	1.144	32.25	0.983	15
	2	0.072	1.592	33.25	0.816	11
	3	0.062	2.008	31.75	0.782	19
	4	0.348	1.019	32.75	0.993	17
	5	0.225	0.941	32.25	0.993	14
	6	0.519	0.819	34.25	0.984	6
	7	0.167	0.439	34.25	0.999	6
	10	0.014	2.835	32.75	0.906	4
	13	0.075	0.247	33.25	0.989	-6
	14	0.067	2.319	34.25	0.980	3
	15	0.044	0.143	33.25	1.000	3
	17	0.150	0.589	32.75	0.997	2
	18	0.005	3.048	34.75	0.738	-5
	Hot	3	1.234	0.803	32.25	1.000

comp- laint	6	0.227	0.698	32.25	0.995	6
	8	0.061	0.524	31.75	0.980	1
	9	0.015	4.008	32.75	0.963	8
	13	0.101	0.205	31.25	0.918	-6
	15	0.091	0.194	31.25	0.985	3
	16	0.001	7.047	30.25	0.958	11

Simulation

The purpose of simulation is to find out the optimal control parameters for the control of indoor thermal environment considering room occupants' temperament type. Because those who are more likely to complain will obviously complain more times during indoor thermal environment control, which leads to the control of being dominated by these "complaining-likely" people. A solution for this issue is to set a specific complaint probability threshold P_0 for each person considering their temperament type. The person who gets a higher score of sanguine temperament is more likely to complain, therefore a higher P_0 value is used to prevent the tendency of "complaining lovers" becoming leading roles in the indoor thermal environment control. The simulation here is used to find out the optimal complaint probability threshold P_0 .

Simulation model

The simulation model was built in the environment of Matlab Simulink. The model includes the following 9 parts, as shown in Figure 4.

1) Room thermal dynamics

This model is used to simulate the thermal dynamics of indoor environment. The inputs are the heating/cooling power of the Air-conditioning (AC) system and the climate data. The outputs are the room air temperature. The thermal dynamics are simulated using the indoor temperature differential equation.

2) Controller

This module is responsible for simulating the control commands of on/off of the AC. With the deviation between the air temperature and the temperature setting, Proportional, Integral and Differential (PID) logic is used to calculate the duty ratio of the AC.

3) AC system

This module is used to simulate the heating/cooling power provided by AC system according to the duty ratio output from the controller module.

4) Skin temperature

Human body thermal balance model is used to predict a user's skin temperature given the room air temperature, metabolic rate, and clothing level.

5) Thermal complaint probability

Using of the cold/hot complaint probability model described former, the complaint probability P of an user can be simulated given the skin temperature output from the skin temperature module.

6) Complaint probability threshold

The complaint probability threshold P_0 is calculated according to the scores of users' sanguine temperament type.

7) Complaint

When the complaint probability from the thermal complaint probability module is larger than the threshold P_0 , a complaint vote might occur with the complaint probability.

8) Room temperature setting

Fuzzy control logic is used to give out the room temperature setting given the deviation of thermal complaint probability P from the threshold P_0 and the thermal complaint probability change rate with time $\partial P / \partial \tau$.

9) Thermal complaint probability model update

This module is used to update the probability model according to users' hot/cold complaints and skin temperatures by an on-line learning algorithm.

Figure 4: Simulation model for optimizing the control parameters of indoor thermal environment considering users' temperament type

Simulation results

The simulation results of the typical control process are as shown in Figure 5.

Figure 5: Simulation result of a typical control process

In this simulation, the user's sanguine temperament score is 3, and the comfort skin temperature is 33°C.

From Figure 5, it can be seen that:

- 1) The indoor air temperature was slightly high in the first 15 minutes. Accompanying to the control progress, the temperature tended to be stable at around 26.3°C.
- 2) In the first hour, 5 hot complaints submitted.
- 3) The complaint probability was high at the first hour. With the decrease of indoor air temperature, the probability became small.
- 4) After about 6000 seconds, indoor air temperature was stable at around the set point. Skin temperature was lower than hot complaint threshold and users' complaint probability was around 0.

The results show the feasibility of the control method based on the cold/hot complaint probability model and the simulation model is feasible for further study of the optimal control parameters.

Optimization of the control parameters

The optimization objective is to find out an optimal complaint probability to make the indoor thermal environment to be controlled as comfortable as possible to all occupants and at the same time to save AC energy. The persons having a certain temperament score will generate more complaints with the complaint probability threshold P_0 getting bigger, while the AC system's energy consumption gets smaller. In other words, the greater complaint probability threshold P_0 is, the lower the energy consumption and the more user complaints are. The lower the energy consumption means less cost and the more user complaint will cause productivity decrease and economic loss. Therefore, there exists an optimal complaint probability threshold that can balance the economic benefit and loss. This paper uses the ratio of economic

benefit to economic loss as the optimization objective. The optimization objective function is shown in Equation 4 to 7 using the Gross Domestic Product (GDP).

$$\text{Objective: Max } \frac{\Delta GDP_E}{\Delta GDP_W} = \frac{\text{Cost saving by energy conservation}}{\text{Economic loss by productivity decrement}} \quad (4)$$

$$\Delta GDP_E = \frac{\text{Energy saving}}{\text{Energy use per GDP}} \quad (5)$$

$$\Delta GDP_W = \Delta PD \times \text{GDP per capita} \quad (6)$$

$$PD = 1 - (0.1647524t - 0.0058274t^2 - 0.0000623t^3 - 0.465328) \quad (7)$$

The economic benefit ratio is defined as $\Delta GDP_E / \Delta GDP_W$, which is the ratio of the economic benefit brought by energy saving of AC system to the economic loss caused by the decrement of productivity because of discomfort of indoor thermal environment. The room occupants' productivity change accompanying to the room temperature is shown in Equation 7, which is proposed by Seppanen et al. (2006).

The optimization problem is solved by traversing all possible values of thermal complaint threshold P_0 by simulation to find out the optimal one. The simulation results for the optimization of the thermal complaint threshold P_0 for the people with different temperament scores. The travers simulation results are shown in Figure 6.

From the simulation results shown in Figure 6, the optimal value of thermal complaint threshold P_0 related to different sanguine temperament scores can be determined. Then for the convenience of field application, the optimal discomfort complaint probabilities are fitted by a linear formula. The fitted formula is shown in Equation 8. Thus the optimal control parameter of thermal complaint threshold P_0 can be determined with a simple rule, which is convenient for field application.

$$P_0 = 0.0036s + 0.2546 \quad (8)$$

Conclusions

This paper Studies indoor thermal environment control considering human temperament type. A model for predicting the probability of submitting discomfort thermal complaints using skin temperature and people's sanguine temperament scores is developed for optimizing the thermal environment control parameters. The performances of indoor thermal environment control base on discomfort thermal complaints probability were simulated with different sanguine temperament scores in Matlab Simulink environment. Optimal control parameters, i.e. the threshold of discomfort complaint probability considering temperament type is determined by simulation. Based on the optimal results, a simple linear equation between the optimal complaint thresholds and the scores of sanguine temperament is fitted. The method proposed by this paper is useful for field application to achieve optimal control of indoor thermal environment considering people's temperament with a simple rule to achieve both energy saving of AC system and prevent economic loss caused by productivity

Figure 6: Optimization results of complaint thresholds for the people with different temperament scores

decrement because of uncomfortable thermal environment.

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