Optimization Method of Thermal Comfort and Energy Saving Based on Individual Sensation Estimation

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Abstract: In office-occupied spaces, the ratio of energy consumption by air-conditioning and lighting that maintains the environment comfort accounts for about 70%. On the other hand, many people claim being dissatisfied with the temperature of the air conditioning. Therefore, there is concern about the work efficiency reduction caused by current air-conditioning control. In this research, we propose an automatic control system that both improves the energy saving and the thermal comfort of all indoor users by quantifying individual differences in thermal comfort from biological information, base on which optimal settings of both air-conditioning system and wearable system that can directly heat and cool individuals. Simulation results in various environments demonstrated the efficacy of proposed system for both energy saving and comfort maximization.

1. Introduction

In office spaces, air-conditioning accounts for the majority of energy consumption. On the other hand, several surveys reveal that a lot of people claim being dissatisfied with the thermal office environment, leading to productivity decrease [1]. Indeed, despite decades of research and the undeniable progress, thermal comfort delivery in ode buildings is still marred by indecencies both in terms of its quality and in the amount of energy it consumes [2]. Despite the dedicated energy resources, thermal comfort in the building is lacking. A survey of buildings in the US, Canada, and Finland found that only 11% of the buildings achieved the recommended thermal comfort satisfaction rate [3]. These results concur with the findings of the International Facility Management Association (IFMA) that pinpointed a high level of complaints about thermal discomfort in buildings[4]. Most thermal provision systems are based on the Predicted Mean Vote / Predicted Percentage of Dissatisfied (PMV/PPD) model that prescribes isothermal settings for all building occupants [5]. Although it performs well when its assumptions are met, some of its premises are ignored in practice [6]. Besides, the rationale of thermal neutrality is contested as a meretricious endeavor since, in reality, people prefer non-neutral conditions [7].

Also, in Japan, a comfortable lifestyle and environment realized by abundant electric power are being questioned by energy consumption reduction policies. In summer 2005, the Government of Japan, through the Agency for Natural Resources and Energy, started the "cool biz" campaign, which recommends setting room air-conditioner temperature to 28°C for energy-savings promotion [8]. Though before "cool biz" start the average room temperature of about 16 thousand office buildings in the Tokyo metropolitan area was 25°C, most companies respect this guideline. However, according to several surveys, it has been shown that it results in increased thermal dissatisfaction and a reduction in productivity [9][10]. Moreover, this has been accompanied by an augmentation of heatstroke risk due to not only hot but also humid summer in Japan. According to the Japan Meteorological Agency, more than 70 summer days exceed a daily temperature of 30°C, while the average relative humidity is about 70%. When the air temperature is 30°C and relative humidity 70%, the Wet Bulb Globe Temperature (WBGT, a measure of heat stress) is 29°C, which correspond to a state of strict vigilance according to the heatstroke prevention regulations.

Since it depends on personal sensation, in dynamic community spaces such as co-working or co-living spaces, it is by definition not possible to satisfy the thermal comfort of all the users of this community with one single setting of the air-conditioning system [11], creating thermal dissatisfaction for everyone in the community. Such, it is obvious that a comfortable thermal environment in co-working spaces cannot be realized using only the Global Heating and Cooling System (GHCS) such as the air-conditioner.

On the other hand, many researches on the effects of thermal stress deal with heat stress. Extreme temperatures or long exposure to less than ideal weather can change core body temperature and impact homeostatic control, or the body's ability to maintain its temperature. As the body works harder to maintain healthy core temperature by reallocating resources like water and energy, the brain is deprived of these same resources and one's ability to think declines [12]. Several researches reported that both local cooling and warming affect physiological indices variations [13][14][15]. Effective energy saving technology for direct temperature-conditioning of the human body has been proposed, and Peltier elements based portable system that can both cool and warm neck has been developed [16][17]. Though the comfortable environment is different among individual and it can be different in same people, but different conditions, current system temperature control algorithm depends only on environment conditions and not wearer's.

In previous work, we have demonstrated a model that can detect thermal comfort state of a user from heart rate variability indices [18]. Therefore, we propose an automatic control system that both improves the energy saving and the thermal comfort of all indoor

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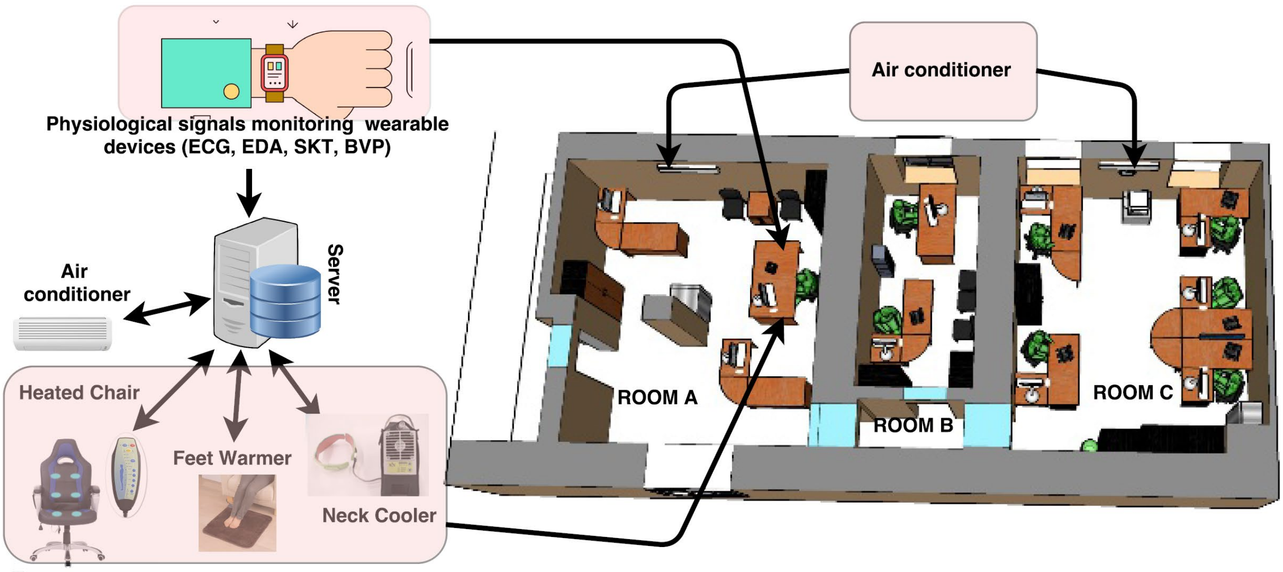

Fig. 1 Schematic of the proposed system

users by not only combining GHCS with an Individual Heating and Cooling System (IHCS) that can directly heat and cool individuals but also by quantifying individual differences in thermal comfort from biological information to optimize the combination (Fig. 1).

2. Method for Individual Comfort Estimation

To be able to build an algorithm for achieving both energy saving and thermal comfort for all the users, it is necessary to model respectively the power consumption and the thermal comfort of the user.

As a method of evaluating the user's thermal comfort, we propose the Sensation Discomfort Index (SDI). SDI is calculated based on adding the individual difference of user's thermal comfort and correction of IHCS to conventional Discomfort Index which defines the environment's thermal discomfort as in equation (1). Where $D_p(i)$ is the individual difference of user i, $D_n(i,TD)$ the correction by IHAC for user i, and D the indoor discomfort index defined in equation (2), where RH is the relative humidity and t the dry bulb temperature. A value of D between 65 and 70 is said to be the most comfortable, such we define this range as the maximum thermal comfort range (MTCR).

$$D_f(i,D) = D + D_p(i) + D_n(i,TD) \qquad (1)$$

$$D = 0.81t + 0.01RH \times (0.99t - 14.3) + 46.3 \qquad (2)$$

To evaluate the power consumption, we use the Total Heat Consumption (THC) calculated by adding GHCS and IHCS heat consumptions. The GHCS heat consumption is calculated by adding the amount of heat held by the air, the amount of heat input from the outside, and the amount of heat generated by the users as in equation (3). Where α is GHCS load, H_v is the target temperature and humidity, H_f is the heat from the outside, and H_p the heat generation of the people.

$$H_e = \alpha |H_v - H_f - H_p| \qquad (3)$$

Besides, we define the thermal comfort error as the absolute value of the difference between the user's SDI and the nearest boundary of the MTCR. Since the Sum of Error of All Users (E_s) and THC can be uniquely determined by the Target Discomfort Index (TDI) in the room, we defined the optimum setting to be the conditions that minimize both E_s and THC as described in figure 2. Therefore, we examined the change of E_s and THC according to the change of the SDI. The results showed that the optimum setting is the SDI that has the smallest absolute difference with the current DI in the room within the MTCR.

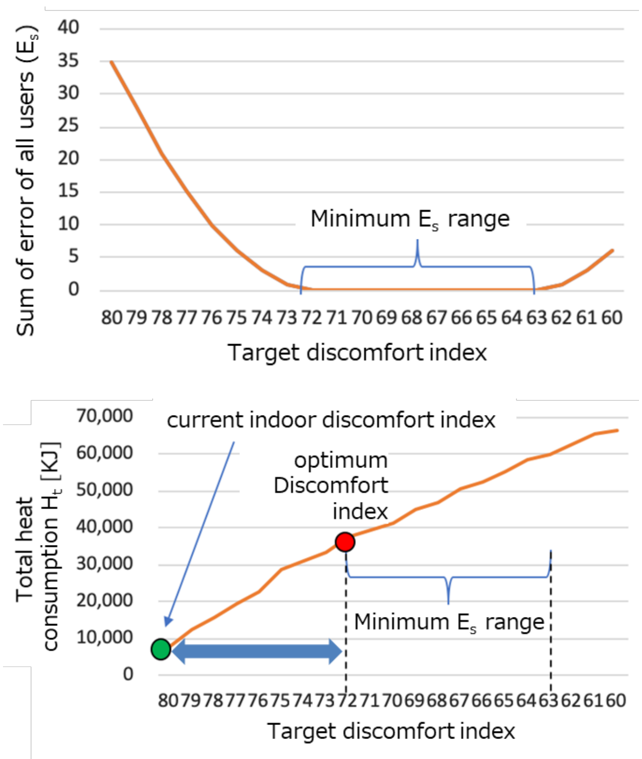

Fig. 2 Method to detect the optimum target discomfort index from the change of E_s (top) and TDI (bottom) regarding environment discomfort index

3. Evaluation of efficacy by simulation

We conducted a simulation under the following three conditions: using only GHCS, using only IHCS, and the proposed system. The simulation parameters were set as following.

- Each system is operating for 1 hour.
- The standard volume of the room for the number of users was set as shown in table 1.
- The outside temperature and humidity were set to 30°C/60% for cooling condition and 12°C/60% for heating condition.
- We defined a correction model of the sensational discomfort index due to individual differences in thermal comfort such SDI can vary in seven levels from -3 to +3 compared to the environment thermal discomfort index. Indeed, A survey on 29 persons of individual differences in temperature preference showed that there were large individual differences, with a difference of 7.2 °C between the maximum and minimum temperatures [19]. The individual differences were simulated according a normal distribution.
- We defined a correction model of the sensational discomfort index due to the use of IHCS, based on the correction function of the IHCS prototype developed in [20]. In this study on 24 persons in a room at the same humidity (60%), when the temperature gradually increases, the average temperature at which persons start feeling discomfort was 27.3°C when wearing the IHCS, and 31°C when not.

Table 1. Standard volume of the

Nb users	Room vol. [m^3]
5	172.3
10	344.5
15	516.8
20	689.0
25	861.3

The results, as shown in figure 3, revealed that the power consumption reduction ratio of using the proposed system compared to using only GHCS increases with a larger indoor volume and fewer indoor users (30% maximum in cooling and 10% maximum in heating).

Concerning comfort optimization, as shown in figure 4, in the case of using only GHCS or IHCS, E_s increases proportionally with the number of users. On the other hand, in using the proposed system, resulted in keeping E_s to 0 all the time.

This results suggested that it is possible to realize both comfort improvement and energy saving of all the users in the room by using the whole air conditioning and heating device and the individual air conditioning and heating device together.

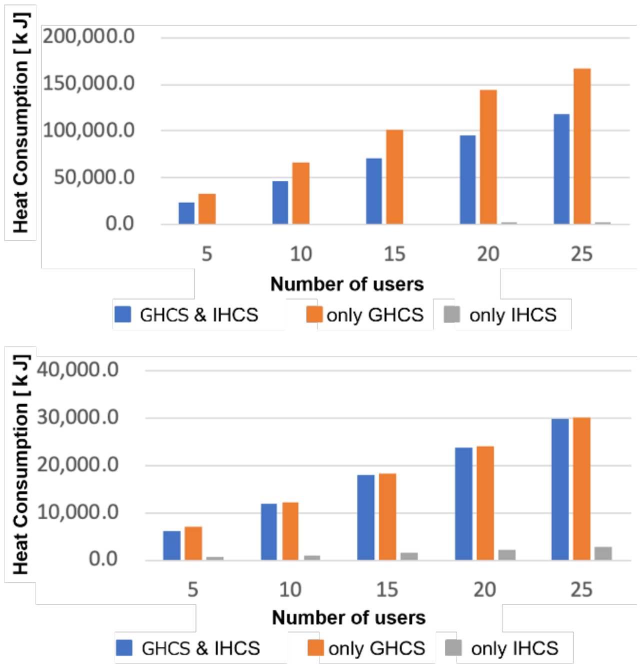

Fig. 3 Total heat consumption in cooling (top) and heating (bottom) conditions of each system depending on the number of users in the room

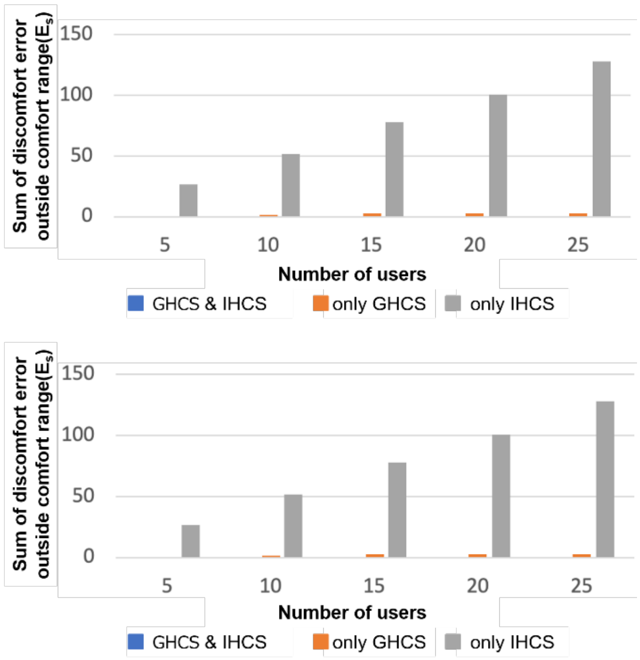

Fig. 4 Sum of discomfort error outside comfort range (E_s) in cooling (top) and heating (bottom) conditions of each system depending on the number of users in the room

4. Conclusion

In the investigation of a control method that can improve both thermal comfort and energy saving for all users of a co-working space, we proposed a model of thermal comfort of the user and power consumption based on the sensation of discomfort index and heat consumption. From the relationship between the thermal comfort sensation of the user and heat consumption depending on the target discomfort index of the room, we have established a method for deriving the indoor target discomfort index for achieving both thermal comfort and energy saving. Simulation results demonstrated that proposed solution enables 30% and 10% maximum power consumption reduction compared to using only GHCS respectively in cooling and heating conditions, while keeping all users in comfortable range, which is not possible using only GHCS or IHCSs.

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