Process Control of Personalized Heating

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Abstract

Personalized conditioning systems represent one of promising solutions for two major problems in current indoor environment – high energy consumption and unsatisfactory thermal comfort. As personalized conditioning focuses on a small space around a single person, it can better and more effectively satisfy the individual needs for thermal comfort than a traditional HVAC system. Personalized conditioning systems that have been tested rely mostly on control by user interaction, i.e. the users have to decide on the level of cooling or heating. This can lead to decreased comfort or increased energy consumption due to incorrect use of the system. This paper presents a novel method of process control of personalized heating based on human thermophysiology. The new control method is compared with user interaction and fixed setting of personalized heating system consisting of heated chair and heated desk and floor mats. Different control strategies for personalized heating were tested with 13 human subjects in a climate chamber under operative temperature of 18 °C for 90 minutes. The test subjects evaluated their thermal comfort every 15 minutes via a computer based questionnaire. As skin temperature of the hands was previously identified as a good predictor of cool discomfort under uniform conditions, it was tested in this study as a control signal for personalized heating.

Thermal comfort and energy use with personalized heating are compared in the results section. Personalized heating improved thermal comfort in all test cases. No significant difference was observed between user interaction, fixed setting, and automatic control.

Keywords: Control, Human subjects, Personalized heating, Thermal comfort, Thermophysiology

1 Introduction

The building sector nowadays accounts for 40% of the primary energy consumption in EU and US (Pérez-Lombard et al. 2008). Most of this energy is spent on providing a comfortable indoor environment by heating, ventilation and air conditioning (HVAC). Current standards for designing the indoor environment such as ISO EN 15251 (2007) prescribe controlling the indoor environment in a narrow range in order to ensure thermal comfort. However, narrowing range of indoor air temperatures is energy demanding and does not lead to higher thermal satisfaction (Arens et al. 2010).

Especially in the office environment Personalized Conditioning System (PCS) is one of the promising ways how to improve thermal comfort and meanwhile reduce energy consumption. PCS brings ventilation, heating, and cooling closer to the user and allows to adjust the microenvironment to suit individual needs. Meanwhile, energy is deployed only at the place of actual need and the background environment can be controlled in more
relaxed manner. This way, energy can be saved due to higher effectiveness of the whole conditioning system.

A number of PCS have been recently developed and tested. Much more attention has been paid to personalized ventilation and cooling rather than to personalized heating (Veselý & Zeiler 2014). Nevertheless, some studies have already proven that personalized heating can improve thermal comfort (Melikov & Knudsen 2007; Watanabe et al. 2010; Zhang et al. 2010; Pasut et al. 2014) and also has potential to reduce the overall heating demand (Zhang et al. 2010; Foda & Sirén 2012; Verhaart et al. 2015).

Most of the researched PCS were controlled solely by user interaction, which can potentially lead to problems with thermal comfort, such as overshoots or delayed reactions, as well as worse energy performance due to inefficient operation. As the hand and finger skin temperature relates to thermal comfort in cool environment, it seems to be a promising control signal for an automated control. The study investigates such an automation of the control process and tests it alongside with user interaction.

2 Methods
2.1 Personalized Heating System
The tested personalized heating system consists of a heated chair, a heated desk mat, and a heated floor mat (Figure 1). The effectiveness of these heaters was tested in another yet unpublished study (Veselý et al. 2016). The maximum power of the heaters is as follows, heated chair: 36 W, heated desk mat: 80 W, and heated floor mat: 100 W.

![Heated chair (left), heated desk mat (middle) and heated floor mat (right)](image1)

Personalized heating system in some of the test cases was user controlled (Figure 2) and the settings were logged with an interval of 2 seconds.

![User control over personalized heating system](image2)
2.2 Climate Chamber and Environmental Conditions
Experiments were conducted in a climate chamber of Unit of Building Physics and Services, Eindhoven University of Technology, The Netherlands. The climate chamber is a well thermally insulated room of dimensions 3.6 x 5.7 x 2.7 m³. It allows for a precise control of the indoor environment, namely air movement, air temperature, and temperatures of all surrounding surfaces.

During this experimental phase the climate chamber was set to maintain both air and mean radiant temperature at 18 °C. As mixing ventilation was used the air movement in the occupied zone was negligible and can be assumed of up to 0.15 m/s. The subjects performed an office work resulting in metabolic rate of 1.2 met and they were instructed to wear clothing ensemble with insulation of 0.7 clo (common winter indoor clothing). These background conditions result in PMV of -1.5 and corresponding PPD of 50 %.

Two user desks (Figure 3) were set up in the climate chamber. Both user desks were equipped with a computer screen, a keyboard, and a mouse. The test subjects connected their laptops to the provided equipment at the beginning of each session.

Figure 3 One of the two user desks in the climate chamber

2.3 Subjects
Thirteen healthy university students (seven males and six females) volunteered as test subjects. Their anthropological data are listed in Table 1.

<table>
<thead>
<tr>
<th>Height [m]</th>
<th>Weight [kg]</th>
<th>Body mass index</th>
<th>Age [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.79</td>
<td>81.1</td>
<td>25.1</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.12</td>
<td>26.8</td>
<td>5.8</td>
</tr>
</tbody>
</table>

2.4 Procedure
Four test cases as shown in Table 2 were tested and all test subjects experienced all test cases. The same personalized heating system was used in all test cases except for the reference. The test cases ‘Fixed’ and ‘Auto’ were based on results of a pretest with 9 test subjects. In test case ‘Fixed’ the average setting from the end of the pretest session was set
for the entire test. The ‘Auto’ case was based on correlation of the settings of each heater with the hand skin temperature. The settings are presented in the results chapter.

Table 2 Test cases

<table>
<thead>
<tr>
<th>Test case code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>Reference case (i.e. no personalized heating applied)</td>
</tr>
<tr>
<td>User ctrl</td>
<td>User controlled personalized heating</td>
</tr>
<tr>
<td>Fixed</td>
<td>Fixed settings based on average settings from the pretests</td>
</tr>
<tr>
<td>Auto</td>
<td>Automatic control based on hand skin temperature</td>
</tr>
</tbody>
</table>

Each session comprised 30 minutes of warm accustomization (i.e. just outside of the climate chamber) and 90 minutes of exposure. During the accustomization period the skin temperature loggers were attached. During the exposure the subjects performed ordinary office work on a computer. The subjects were asked to fill in a questionnaire regarding their thermal comfort every 15 minutes within the exposure.

2.5 Measurements – Subjective Evaluation

During the experimental sessions the subjects evaluated their thermal comfort via a java-based app (sample screenshots shown in Figure 4). This app includes questions regarding the subjects’ clothing, thermal sensation, thermal comfort, and wellbeing. Thermal sensation and comfort questions are asked as overall and in particular for neck, head, arms, hands, legs, and feet. An ASHRAE 7-point scale is used for evaluation of thermal sensation and a comfort scale (from clearly comfortable to clearly uncomfortable with separation of just comfortable/just uncomfortable in the middle) for thermal comfort.

![Thermal comfort questionnaire app](image)

2.6 Measurements – Environmental Data

The thermal environment in the climate chamber was continuously monitored during all experimental sessions. This includes measurements of air speed and air temperature at the heights of 0.1, 0.7, and 1.1 m (standard heights for a sitting person) as well as the relative humidity and globe temperature in the occupied zone of the room. All environmental data were logged with an interval of one minute and measured in compliance with ISO 7726 (ISO 1998).
2.7 Measurements – Physiology
In order to investigate the effect of personalized heating on human physiology skin temperature was measured on 14 locations on the body by iButtons (van Marken Lichtenbelt et al. 2006) as shown in Figure 5. Digital thermometer DS18B20 was used to measure the hand temperature (location “I” in Figure 5) additionally to iButton. This allowed for real-time reading of the temperature that can be used in a control loop.

3 Results
3.1 Settings of personalized heating system
A pretest with 9 test subjects was used to extrapolate settings of the personalized heating for test cases ‘Fixed’ and ‘Auto’. The pretest followed the same procedure as the normal test and test subjects controlled the personalized heating by user interaction. An average setting from the end of the pretest was used as a fixed setting for the whole exposure of test case ‘Fixed’. These settings were as follows, heated chair set at 50 % of its max power, heated desk mat at 65 % of its max power, and heated desk mat at 70 % of its max power.

Proportional control based on hand skin temperature was used in test case ‘Auto’. The control equation was derived from linear correlation of the hand skin temperature and the user controlled power of the heaters in the pretest (heated desk mat shown in Figure 6). This correlation resulted in $R^2$ values of 0.62 for the heated chair, 0.90 for the heated mat, and 0.86 for the heated floor mat. The derived control curves are shown in Figure 7.
3.2 Thermal sensation and comfort

The average overall thermal sensation over the whole exposure is shown in Figure 8. At the beginning of the exposure the test subjects felt about neutral because of the accustomization right outside of the climate chamber. In the ‘Ref’ case thermal sensation dropped under slightly cool at the end, while in other test cases it was maintained above neutral by personalized heating system.

Figure 9 shows the thermal sensation and comfort at the end of exposure. The difference between the ‘Ref’ case and the other cases is significant (p < 0.05) for both, thermal sensation and comfort. The response to ‘Fixed’ seems to be more scattered than for ‘User ctrl’ and ‘Auto’. However, no significant difference was found among these three test cases.
Figure 9 Thermal sensation (a) and comfort (b) at the end of exposure (boxplots of all 13 test subjects)

Figure 9 shows the thermal sensation and comfort at the end of exposure. The difference between the ‘Ref’ case and the other cases is significant (p < 0.05) for both, thermal sensation and comfort. The response to ‘Fixed’ seems to be more scattered than for ‘User ctrl’ and ‘Auto’. However, no significant difference was found among these three test cases.

3.3 Energy consumption

Figure 10 depicts the energy consumption of the personalized heating system under the different control modes. The lowest energy consumption was observed in the test case ‘User ctrl’.

Figure 10 Energy consumption of personalized heating averaged per person over the whole exposure (90 minutes)

4 Discussion

The finger and hand skin temperature was previously identified as a good predictor of cool discomfort (Wang et al. 2007). It could be expected that the moment of cool discomfort is the moment when people turn on or increase the power of personalized heating when available. Wang et al. (2007) reported that approx. 30 °C of fingertip temperature seems to be a threshold for a risk of cool discomfort. This is in line with our observation on the relation of hand skin temperature and the setting of personalized heating. The test subjects
tended to turn on the system at hand skin temperature of about 30 °C and then increase the power as the hand temperature was decreasing.

As expected personalized heating clearly improved thermal comfort. However, no significant difference was observed between the three tested modes of control. Zhang et al. (2010) reported that the user interaction is in some cases a preferred option over fixed setting, but this happens only in more extreme thermal conditions, which can explain why we did not observe a similar trend.

The energy consumption of the presented personalized heating system was the lowest when user controlled. However, this was probably influenced by rather short exposure and the fact that most of the test were gradually increasing the heating power within a first third of the test in order to find a comfortable setting. It also has to be noted that the fixed setting, which appears to perform the worst from energy perspective, would benefit from presumably lower cost of the system and its maintenance.

The test subjects were also asked for general comments on personalized heating control. Some claimed that they preferred user interaction because they want to be in charge, while others prefer automatic control because they want to focus just on their work. This implies that a flexible system combining user interaction with automatic control might be needed. One of the possible options for such a combination is shifting the set points of the automatic control via user interaction. This is recommended for further research.

5 Conclusions
The presented personalized heating system significantly improved thermal comfort. No significant difference in terms of thermal comfort was observed between three modes of control of personalized heating, i.e. between user interaction, fixed setting and automatic control.

User controlled personalized heating used slightly less energy than the other two modes. The following issues are recommended for further investigation:

- Uniformity of the thermal environment, when personalized heating is applied.
- Possible individualizing of the automatic control of personalized heating.
- Possible combination of user interaction and automatic control of personalized heating.

References


**physical quantities**, Geneve, Switzerland.


