THE HUMAN LEADING THE THERMAL COMFORT CONTROL

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ABSTRACT

Many buildings were designed and calculated by advanced software tools and simulation tools. However in real practice these buildings do not achieve the calculated energy efficiency, but use up to 40 to 50% more energy. One of the reasons for the discrepant ion between designed performance and real performance is the human behavior of which no real adequate integration into the design tools exists Therefore new design approaches are needed to implement the real behavior of occupants of buildings. Human-in-the-loop Technology is developed; a technology to implement user behavior. By starting from the human perspective and use available and new technology, we determined the critical performance indicators for the perceived human comfort. To further optimize the performance of these systems, further development is done into the possibilities and use of infra red heating systems for individual comfort control on workplace level.

INTRODUCTION

There is growing evidence that many, especially sustainable, designed buildings do not, in practice, meet the intended levels of energy performance (Tetlow et al. 2012). The subject of energy has become increasingly contentious with the current energy prices and the strict emissions targets for the future (CIBSE 2012). In fact, energy consumptions are frequently two times the design expectations; this discrepancy has been termed the 'performance gap' (Bordass et al. 2004). This situation is the result of the applied energy modeling calculations conform building regulations and rarely consider the real in-use performance and, in particular, the actual behaviour of the building occupants (Tetlow et al. 2012). Designers look at regulated loads whereas facilities managers look at the whole energy bill including unregulated loads, representing the real occupants' behaviour(CIBSE 2012). Traditionally, during the design process the construction industry has considered the building occupants often superficially. Efforts to reduce the energy consumption caused by the building occupants have largely revolved around the 'information deficit model' which assumes that people will both interpret information as intended and act rationally to modify their behaviour accordingly. This somewhat simplistic approach to the behaviour of the building users has been shown to be largely ineffectual (Owens & Driffill, 2008) and there is now a growing realization that delivering sustainable, healthy buildings will require a greater appreciation of how the occupants interact with their environment (Tetlow et al. 2012). Clearly, the building occupants behave more complex than current standard design models allow for. The human behaviour can influence the energy consumption by more than 100% (Brohus et al. 2010, Parys et al. 2010), so therefore it is necessary to incorporate the human needs better in the control strategies. Sensing, monitoring and actuating systems in relation to the user perception and preferences play the key role in reducing overall energy consumptions in buildings. Optimized process control is a necessity for the improvement energy performance of buildings (Yu et al 2007). Overall the role of the occupant in relation to the energy consumption has found to be important (Haas et al 1998, De Groot et al 2008). Reduction of or optimizing of energy use is often done without really taking in to account the goal of the energy consumption, human comfort. However energy reduction can only be achieved if user comfort is individually addressed (De Groot et al. 2008). Trying to optimize energy efficiency without addressing occupant comfort is not going to work (Nicol 2007). With smart energy efficient buildings the relation between human behaviour and energy consumption has become significant, and should be looked into by applying Building Energy Management Systems (Pauw et al 2009).

THE 'HUMAN-IN-THE-LOOP' APPROACH

One of the primary objectives of a heating, ventilation and air-conditioning system is to provide a thermally comfortable environment. A comfortable indoor environment for all the people in a building is difficult to reach because of individual differences between persons. Based on literature it is concluded that individual differences, including: age (Oeffelen 2007), gender (Karjalainen 2007, Choi et al. 2010), fat (Zhang et al. 2001), metabolism (Havenith et al. 2002) and clothing resistance (De Carli et al. 2007), are of importance for the individual experienced thermal comfort. However, nowadays still the Fanger comfort model (Fanger 1970) is mainly used to determine the (thermal) comfort inside office buildings. Individual preferences are not taken into account in this model. A lot of effort has been taken to design energy efficient HVAC systems. However, in practice the intended comfort level of these HVAC systems is not achieved, resulting in more sickness absence and lower productivity of the building occupants. This is mainly due to the fact that the control paradigm for HVAC systems has remained relatively unchanged, namely regulating indoor environmental variables such as air temperature without including the thermal state of the individual occupant in the control loop. The traditional thermal comfort models (see e.g. Fanger 1970) assume that people in buildings are passive recipients that are comfortable or not comfortable dependent of the momentary thermal environment (temperature, airspeed etc.), while others (e.g. Nicol & Humphreys, 1973 and Paciuk, 1990) argue that also occupant behaviour and feedback loops for personal control are essential for modeling indoor climate related man-environment relations (Claessen et al. 2012). For example Boerstra & Beuker (2011) concluded – after an analysis of 20 field studies – that office buildings in which occupants perceive to have adequate control over their indoor climate are more comfortable and have less building related symptoms. Reanalyzing the HOPE database (60 office buildings with over 6000 respondents), Boerstra et al. (2012) found correlations between buildings with more perceived personal control on temperature and increased thermal comfort during winter and with more overall comfort during winter and summer. Furthermore combinations of control options were found to be more effective at reducing the building related symptoms than single control options (except for control on noise). Their findings suggest that more perceived control over indoor environment will improve comfort and health of the building occupants (Boerstra et al. 2012).

HUMAN COMFORT AND COMFORT CONTROL

The most recent research on human comfort looks at local sensations of individual body parts (Zhang et al. 2010) and thermoregulation with skin temperature predictions (Munir et al. 2009). The interaction between indoor environment and skin is for normal office conditions largely determined by the mean radiant temperature and therefore there is a large effect of mean radiant temperature on the energy consumption in a comfort-controlled office (Kang et al. 2010). By optimizing the responses to the individual human comfort differences energy conservations of up to 25% are possible (van Oeffelen et al. 2010). The energy supply to a building must be related to actual dynamic changing comfort needs, behaviour of the occupants of the building and the behaviour of the building itself due the weather conditions. Therefore, more actual information is needed. The application of low cost wireless sensors offers new practical applicable possibilities (Neudecker 2010, Gameiro Da Silva et al. 2010). If so, then energy demand and energy supply could become more balanced and less energy wasted.

Measuring the radiating temperatures by a low cost Infra Red camera should make it possible by image post-processing to estimate energy fluxes and temperature distributions with comfort prediction. Correct temperature distribution measurements could be calculated by remote camera control and thermo graphic parameter correction (Revel and Sabbatini 2010). Thermal comfort for all can only be achieved when occupants have effective control over their own thermal environment (van Hoof 2008). This led to the development of Individually Controlled Systems (ICS) with different local heating/cooling options (Filippini 2009, Wanatabe et al. 2010). Our intention is to design and built an experimental workplace with an individual controlled heating/cooling panel in front of the workplace to test our specific approach to comfort and energy management. The implementation of such detailed dynamic approach to individual comfort control is new.

It is necessary to look more closely to the individuals on working space and personal level. So we do not look only to room temperatures and thermostat settings of heating or cooling devices, but really look into the dynamic parameters related to the individual thermal comfort, the actual occupancy, and the actual parameters of the building services installations and use of appliances.

ANALYSIS OF PERCIEVED HUMAN COMFORT

Literature shows that the hands are the most sensitive body parts for the human thermoregulatory system (Zhang 2003). In addition, upper-extremity skin temperature is a sensitive indicator of the body thermal state in the cooling region (Wang et al. 2007). Studies in the automotive field have shown that facial skin temperature is a measure for overall thermal sensation (De Oliveira et al. 2009). Both the hands and face are directly exposed to the environment and show potential to be remotely sensed.

Recently, individual controlled (HVAC) comfort systems were proposed, which can cope with the individual differences (e.g. clothing behaviour, body fat) between office workers. In addition, these systems focus on the body parts (hands, feet and head) which mainly dictate thermal discomfort in mild cool/warm office environments. A direct conditioning of these parts would be the most effective way to achieve thermal comfort. A set up of such a concept is shown in Fig. 1. The human body can regulate heat flow to the environment by increasing or decreasing the skin blood flow. During mild cool exposure vasoconstriction is the most important thermoregulatory effecter, which can be clearly observed in the upper-extremity region. In addition, the variations in facial skin temperature may also indicate if a person is getting warmer or cooler. The challenge for automatic control of radiant heating is to detect the turning point from a neutral thermal state to a cooler thermal state before the user perceives any cool thermal sensation. The fact that the skin temperature can fluctuate within a range of temperatures without producing any temperature sensation (i.e. the neutral zone) is highly useful in this.

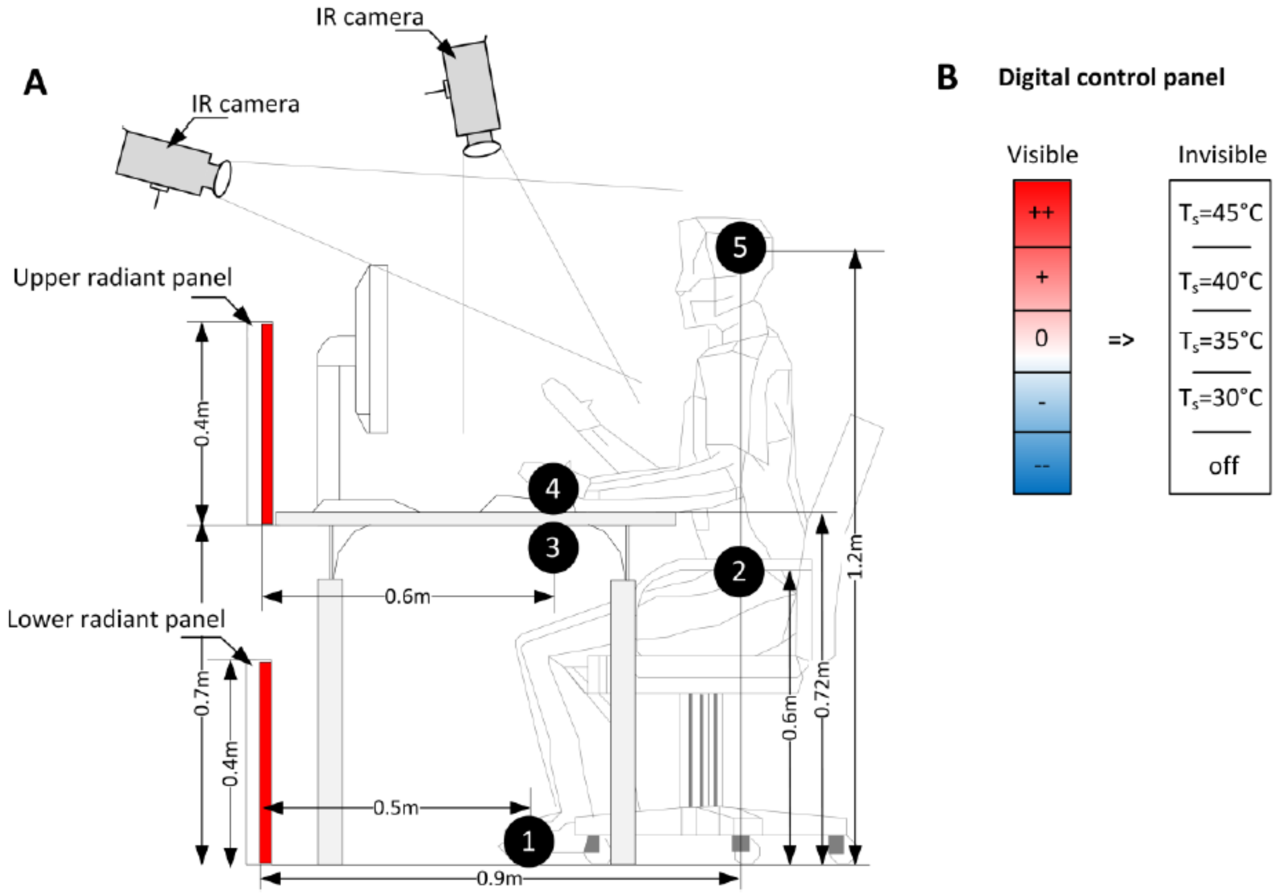

Figure 1. Experimental workplace set-up. for individual thermal comfort(A) local HVAC system consisting of two vertical mounted radiation heating panels, and (B) digital control panel. Two infrared (IR) cameras for skin temperature measurements and measurement positions (black circles) of local comfort parameters, where 1=feet, 2=abdomen, 3=desk, 4=hands and 5=head.

Experiments I: User-control proof-or-principle

A number of user-controlled experiments were performed, in mild cool conditions (Ta=19~20°C), in order to determine if a decreasing trend in skin temperature of the hands or face was observed, before the user performed any heating control action. The only intervention in the individual thermal climate was the use of individually controlled infra red heating panels. The panels were placed vertically in front of the office desk and therefore not optimized to heating the hands, see fig 1. Two human subjects participated in this research. The results ‘proof-of-principle’ demonstrated that the finger skin temperature was a critical performance indicator of the body thermal state in the cooling region. To test whether the finger temperature was actually useful as control signal, the experiments were reversed: from user-control to automatic control. The goal of these user-controlled experiments was to detect a feed forward transition out of the comfort zone, before the user took any control action. Results showed that this transition is quite difficult to detect. Standard fluctuations of 2 °C in finger skin temperature make it difficult to recognize a clear trend out of the neutral zone. Additionally, in some of the user-controlled experiments a decreasing trend in finger temperature is shown before the user had taken any control action. While in other sessions the decreasing trend was recognized too late, which means that subject already had taken a control action to compensate for his cool sensations. In almost all sessions, the radiant heating system was, despite of the maximum panel temperature (set by the user), not able to compensate for the cool whole-body sensations. Skin temperatures of the finger and hand did not return to the comfortable zone.

Experiments II: Automatic comfort control

An improved heating system was applied which radiates the heat more concentrated to the hands. This heating system consists of two incandescent reflector heating lamps (Philips R125 IR250) focusing each on one hand, see Fig. 2.

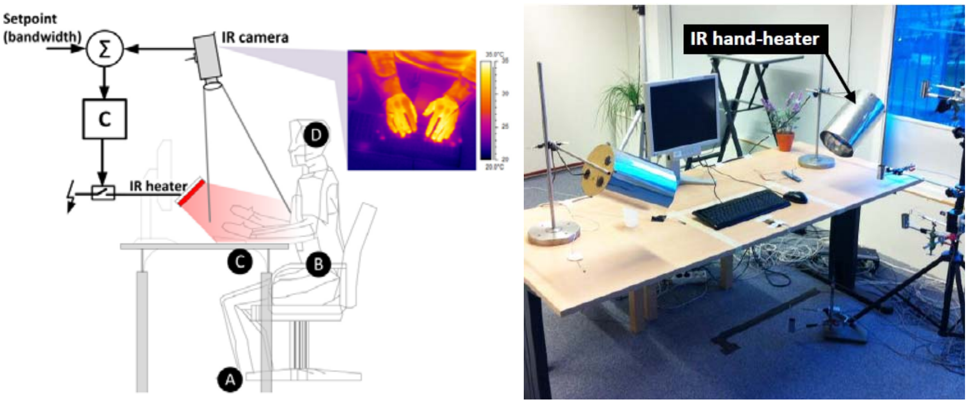

Figure 2. Local heating controlled by subjects' upper-extremity skin temperature, an experimental setting to measure the effect of individual controlled additional radiative heating.

The finger temperature, measured by IR thermography, was tested as feedback control signal for automatic regulation of a radiant hand-heating system by applying different set-points: the small, medium and large bandwidth. The bandwidth is defined as a range of skin temperatures in which the finger temperature was controlled. By controlling the finger temperature in a small bandwidth (Tsk=29-31.5°C), it was possible to feed-forward respond to user thermal preferences (i.e. before cool discomfort occurred), while the basic room air temperature was lowered from 22 to 19.5°C (Fig. 3).

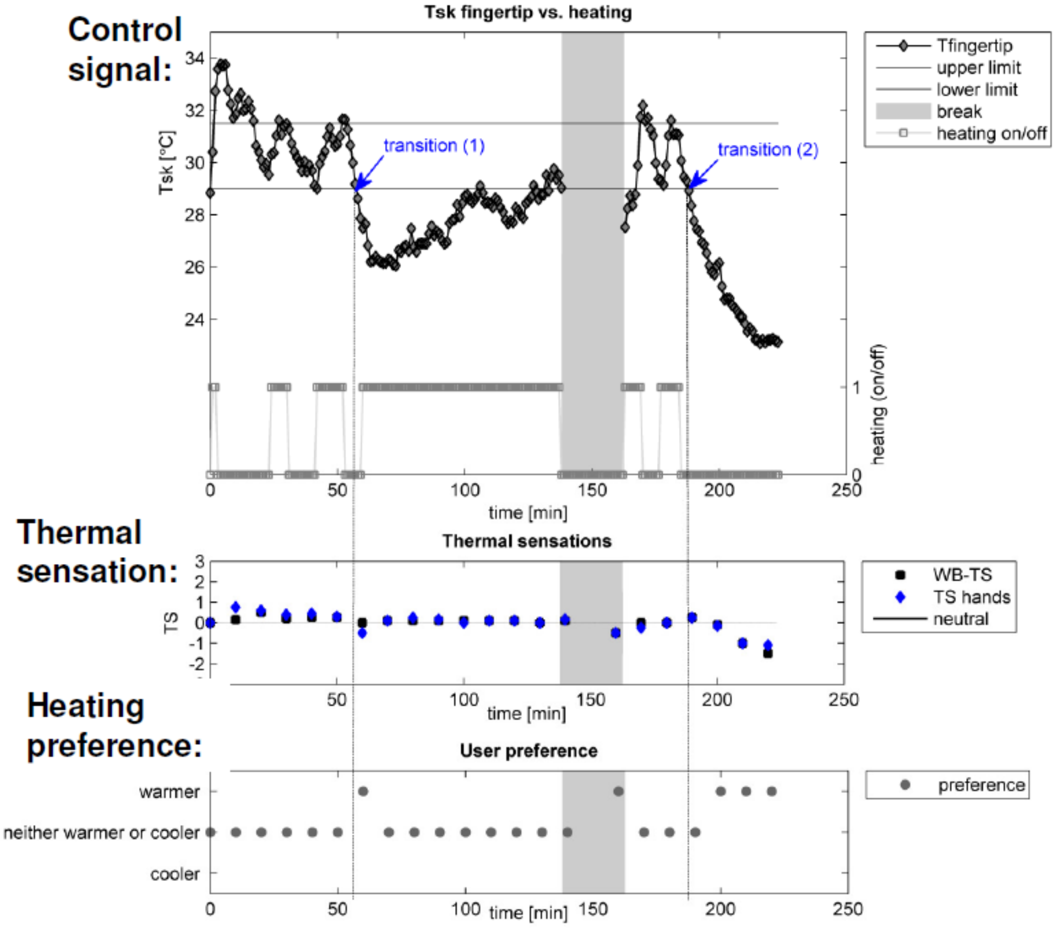

Figure 3. Upper-extremity skin temperature controlled in a small comfort temperature bandwidth with two transitions out of the bandwidth. Fingertip skin temperatures (moving average) versus heating level, whole-body and local thermal sensation, and heating preferences.

The local- and overall thermal sensation of the subjects were maintained at neutral or slightly higher level, and the subjects (n=2) did not prefer any environmental control action. A correlation between the finger temperature and overall sensation was found (r2=0.45, P<0.05). By modeling the preference that arises from the interactions with the user, this small bandwidth might be applicable to other individuals.

DISCUSSION

Where this research did not look at the comfort level by conditioning when the user is present, the building user comfort level should be looked into. The challenge is that the workplace should be right conditioned before the neutral thermal state turns into a cooler or warmer thermal state. When the skin is adapted to a certain temperature, the skin temperature can fluctuate between the borders of the neutral thermal zone without causing any thermal sensation. Wang (Wang et al., 2007) tested persons by exposing them to a slightly cool environment of 19 °C and warm environment of 28.2 °C. In the situation of the slightly cool environment the testes subjects voted their thermal sensation was cold between 10 and 20 minutes. In the warm environment the subjects voted warm after circa 10 minutes. This means that the building service systems must be capable of conditioning the workplace within 10 minutes, before the building user perceives warm or cold;

The achieved energy reduction by controlling the temperature on room level was 16% for heating and up to 28% for cooling compared with the actual situation.

The applied model to calculate the comfort is based on the PMV value. For the actual situation, where an uniform environment is assumed this PMV model could be said to be applicable, where it has the restriction that even with PMV of zero, there is 5% of the building users not satisfied with the environment. For the calculated PMV on room there are some points which can be discussed. This PMV does not take into account that it takes some time before cold conditions are perceived. With the possibilities of the user position detection it should be looked into if the room can be feed-forward controlled, so the building systems start with climatization before the occupant enters the room.

CONCLUSION

This article presents a new control strategy for automatic control of personalized radiant heating in mild cool office environments, by including the human body as sensor in the control loop. The upper-extremity skin temperature, remotely sensed by infrared (IR) thermography, was proposed as feedback control signals. The objective of this control strategy is to save energy, while maintaining thermal comfort of the individual building occupant. Improvement of the energy consumption was made possible by enhancing individual comfort of occupants (individual comfort control strategy) and incorporation of their behaviour (wireless sensor position determination). By starting from the human perspective and use available and new technology, the outcome will be more focused on the ability to understand the critical aspects of the comfort of the end users. With the ‘Human-in-the-loop’ approach more than 20% energy savings can be achieved on heating demand and up to 40% energy savings on cooling demand compared with the actual energy demand.

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