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Simone, Angela; Yu, Juan; Levorato, Gabriele; Olesen, Bjarne W.; Zhu, Yingxin

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THERMAL COMFORT ASSESSMENT OF DANISH OCCUPANTS EXPOSED TO WARM ENVIRONMENTS AND PREFERRED LOCAL AIR MOVEMENT

Angela SIMONE¹,∗, Juan YU², Gabriele LEVORATO³, Bjarne W OLESEN¹, Yingxin ZHU²

¹International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark
²Department of Building Science, Tsinghua University, Beijing, China
³Department of Industrial Engineering, University of Padova, Padova, Italy

*Corresponding email: asi@byg.dtu.dk

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SUMMARY

In warm climate regions the opening of windows and/or the use of desk or ceiling fans are the most common systems used to generate increased airflows that compensate for higher environmental temperatures at the expense of relatively low energy consumption. When using desk fans, local air movement is provided around the upper body part of seated occupant generating a certain cooling effect.

In warm office environments (26°C to 34°C with constant absolute humidity of 12.2 g/m³) the local cooling impact and the possibility to keep comfortable conditions for the seated occupants, commonly adapted to cold climate, were investigated by using thermal manikin, physiological data collection, and subjects’ assessment.

Results show that, also for Scandinavians, comfortable thermal conditions with high acceptability and satisfaction of the thermal environment can be achieved in an office room temperature of 28 °C, and improved a bit if personal control is guaranteed.

INTRODUCTION

Thermal comfort Standards for indoor environments, ISO 7730-2005 and ASHRAE 55-2013, include air movement limits that protect the occupants of being exposed to draught problems and discomfort. They adopted a model that provide a conservative upper limit for air velocity that protects occupants who are sensitive to air movement and occupants who are mostly occupied with sedentary work. However, while the ISO 7730 (2005) recognized that: “People used to working and living in warm climates can more easily accept and maintain a higher work performance in hot environments than those living in colder climates”, ASHRAE 55 (2013) has extended the higher limits levels of air velocities but only under personal control of the occupants. Nevertheless, the limits of air movement are dependent on air turbulence (Tu) and frequencies (fe), while the direction is not considered.

In 1974, by measurements performed with thermal manikins, Fanger et al. (1974) measured higher heat loss when the direction of air movement was directed from the front. The use of the higher cooling effect obtained by the front air flow was supported by Zhou’s (1999) results showing through human subjects’ experiment lower draught rate than the model for seated occupants.
On fields and laboratory studies have been often performed in warm and/or humid climate regions showing that people adapted to warm environments are less sensitive to draught and, as consequences, suggesting that higher air velocity could be used for obtaining neutral environment at higher temperatures at the relatively low expenses of energy consumption. (Yang and Zhang, 2009, Cândido et al., 2010, Cândido et al., 2012, Schiavon and Melikov, 2009, Sun et al., 2013, and etc.). Besides, the occupant’s control on preferred air velocity can provide a higher percentage of people satisfied (Feriadi and Wong, 2004) and an increase of fan usage for cooling at the room temperature increase (Weiwei et al., 2012, Huang et al., 2013).

The present human subjects study focused on the cooling effect of increased air movement in warm environment, on the achievable thermal comfort when personal control is allowed. Heat loss from thermal manikin and skin temperatures helped to evaluate the cooling effect on the participants representing the cold climate adapted population.

**METHODOLOGIES**

In an office-like climatic chamber at the International Centre for Indoor Environment and Energy at Technical University of Denmark (ICIEE, DTU), the preferred air velocity and its effect on the occupants were investigated at warm room temperatures, from 26°C up to 34°C, and at constant absolute humidity of 12.2 g/m³.

27 Scandinavians (11 females and 16 males), born and living in Denmark (average age of 23 ± 10), were performing desk-office activities (1.2 met of estimated activity level) while exposed to a front direct air movement at the upper front body-part generated by a personal desk fan. They wore typical summer ensemble clothes resulting in an average of clothing insulation of 0.54 clo.

The study consisted of 5 study cases as listed in Table 1. The total exposure time of each participant for study case lasted 2 hours. After an adaptation time of 45 minutes, blind of the aim of the experiment, the participants were exposed to a fix constant air speed, randomly changed from 0.6 m/s to 2 m/s (see Table 1), and later invited for 15 minutes to adjust the air speed for achieve their thermal comfort which it was kept fix for the last 15 minutes exposure (see Figure 1). Along the experiment, before each change, the occupants were asked to assess the experimental environment through a questionnaire (Q). Information of the occupants perception about: thermal environment (thermal comfort, thermal acceptability, air movement preference, etc.), air quality (perception of air quality, air humidity, etc.), experienced sick building symptoms (dry eyes, irritated throat and nose irritation, etc.), and etc., were collected.

<table>
<thead>
<tr>
<th>Case Studies</th>
<th>Case to [°C]</th>
<th>RH [%]</th>
<th>&lt;0.2 [m/s]</th>
<th>0.6 [m/s]</th>
<th>1.0 [m/s]</th>
<th>1.5 [m/s]</th>
<th>2.0 [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>26</td>
<td>50</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>28</td>
<td>45</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>40</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>√</td>
<td>-</td>
</tr>
<tr>
<td>D</td>
<td>32</td>
<td>36</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>E</td>
<td>34</td>
<td>32</td>
<td>√</td>
<td>-</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>
The individual preferred air velocities were recorded to be used in the second scheduled experiment with the same participants exposed to two different air flow patterns, constant or simulated natural wind, having as mean air speed the average of the subjects’ choice. However, results of the second part of the subjects study will not be presented here.

Operative- ($t_o$) and air- ($t_a$) temperatures, relative humidity ($RH$) and air velocity ($v_a$) were constantly monitored and recorded in the center of the room and/or at the occupant location. Four local body part skin temperatures (forehead, right scapula, left hand, and right shin) were recorded by the calibrated i-Buttons sensors (±0.1 °C of accuracy) and by the equation reported in ISO 9886 (2003) the total body skin temperature was calculated. Forehead skin point has been chosen instead of the neck as it was considered to be more representative since the local air speed was directed to the occupant’s face. By the all body and forehead skin temperatures, the cooling effect on the occupants was analysed.

Besides, the cooling effect of front directed air flow was evaluated through the thermal manikin, which was exposed at the same room environment at 26 °C, 28 °C and 30 °C. Body parts equivalent temperatures and heat losses were recorded and analyzed.

**RESULTS AND DISCUSSIONS**

The monitored room conditions of the first experimental section, to which the participants were exposed, are reported for study case in Table 2. When considering the actual use of the desk fan, which see 22% in case A and 19% in case B the not usage of desk fan, the average preferred local air speeds was calculated and also shown in table 2.

<table>
<thead>
<tr>
<th>Study-Case</th>
<th>$t_o$ [°C]</th>
<th>$RH$ [%]</th>
<th>$v_a$ [m/s]</th>
<th>Local Preferred $v_a$ ± St.Dev. [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>26.1</td>
<td>50</td>
<td>0.18</td>
<td>0.58 ±0.30</td>
</tr>
<tr>
<td>B</td>
<td>28.1</td>
<td>46</td>
<td>0.19</td>
<td>0.74 ±0.46</td>
</tr>
<tr>
<td>C</td>
<td>29.9</td>
<td>42</td>
<td>0.18</td>
<td>0.87 ±0.45</td>
</tr>
<tr>
<td>D</td>
<td>31.5</td>
<td>41</td>
<td>0.16</td>
<td>1.29 ±0.35</td>
</tr>
<tr>
<td>E</td>
<td>33.5</td>
<td>37</td>
<td>0.20</td>
<td>1.42 ±0.42</td>
</tr>
</tbody>
</table>

The study with the thermal manikin showed that air flow from the desk fan was having a null impact at the lower body parts, a minor impact at the arms and chest, and a major impact at the face. In figure 2 the heat loss variation of the most sensitive body parts and of all body can be observed when warmer room environments occurred (cases A, B, and C) with the increase of local air movement (from no fan use up to 2 m/s).

With the increase of room temperature, the total heat losses were lower and almost null with the increase of air velocity (equal to 30-31 W/m² in case C).
Figure 2. Thermal manikin heat loss of the face and all body, at the study cases A, B, and C.

Similar results were observed by the measured forehead and skin temperatures. In Figure 3 are shown the temperature variations when the occupants were in a warm environment with and without the supportive cooling effect of desk fans. It shows that the preferred air velocities, in the study cases A, B, and C, decreased the forehead temperature of 1.3 °C and the skin temperature of 0.7 °C; while only half of those temperatures difference were noted in D and E.

Figure 3. Average of forehead and all body skin temperatures (±St.Dev.), at all study cases.

When observing the preferred local air flow by the Danish participants, a different behavioral and physical reaction of the human body was indicated. By some statistical analyses it was confirmed that the study cases A, B, and C are unlikely the same than D and E. In fact, the statistics t-test showed that the values of cases A, B, and C resulted significant different than the ones of cases D and E with p-values<0.0001. This result suggested that the case-studies A, B, and C, and D and E, could be separately analyzed as two sub-groups.
As shown in Figure 4 the participants assessed acceptable the air movement in the three study cases with lower temperature with a larger preference for the environment at 28°C. Result that was strongly confirmed by the global thermal acceptability, see Figure 5, where none found the room environment unacceptable. With respect of the occupants, those results support and confirm the range of variability of physical indoor values, reported in ISO 7730 (2005), giving $t_a$ up to 30 °C and $v_a$ up to 1 m/s.

In terms of thermal global assessment the participants expressed their thermal sensation vote (TSV) at the end of each section and, as shown in Figures 6 and 7, the environment of study case B and C can also be considered as office environment to provide to cold climate adapted
people. Moreover, the room condition with 28 °C was the most preferred one by the participants as resulted with lower level of unacceptability and thermal dissatisfaction (PD) of only 4%.

In general the study case B resulted having even better environments than the one suggested for building design in summer conditions by the standard ISO 15251 (2007), here represented by the study case A, regardless the occupant control on local air flow.

**Figure 6.** Thermal sensation votes at different air speed, for all study case

**Figure 7.** Average thermal acceptability during the exposure, for all study case

Those results indicate that it is possible to offset warm sensation within a range of indoor conditions using increased air velocity also for Scandinavians. Higher air velocity and personal control increased the acceptability of the indoor environment at higher air temperatures.
As earlier mentioned, the results of this first experimental section were used for a following study where the same Danish participants were again exposed to the room environment of study cases B and C and to the mean preferred air speed with different air flow pattern. A first analysis showed no significant difference of the cooling effect due to the type of air flow, while the subjects’ assessment indicated a preference for the constant air movement. More about, it can be found in Yu et al. (2014).

CONCLUSIONS

Population of colder countries, as Denmark, can offset the warm sensation and achieve thermal comfort in warm office environment at 28 °C and 30 °C by using desk fans. In particular, the study case at 28 °C could guarantee better environmental conditions than the upper limit operative temperature suggested for building design by the standard in summer, having also the lowest thermal dissatisfaction of 4%. In general, the cooling effect of higher local air velocity that impact on the occupants has not significant difference if constant or simulated natural wind was used. However, personal control and adjustment on preferred air flow played a major role on obtaining and increasing the acceptability of warm environment. Those conclusions support the results earlier found in warm climate regions of perceiving higher air velocity as pleasant toward relatively low energy consumption.

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