Effects of different cooling principles on thermal sensation and physiological responses

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Effects of different cooling principles

on thermal sensation and physiological responses

Lisje Schellen

Windsor 2012
15 April 2012

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UM

Technische Universiteit
Eindhoven
University of Technology
Where innovation starts
Annex 37: Optimal energy/exergy-use will not always lead to an increased comfort level [Juussela, 2003].

Application of low-energy/exergy HVAC systems can result in local discomfort [Prendergast and Erdtsieck, 2003; Isaksson and Karlsson, 2006; Richter, 2007; Hashigushi et al. 2010].

The thermal environments in buildings with low-energy/exergy systems can be more complex due to non-uniformity.

Combined radiant and convective heat transfer play an important role in the assessment of thermal comfort.

Thermal comfort is one of the main requirements to successfully apply low-exergy HVAC systems.
Cooling:
1. Passive cooling through mixing ventilation
2. Active cooling through convection and mixing ventilation
3. Active cooling through convection and displacement ventilation
4. Active cooling through radiation by the ceiling and mixing ventilation
5. Active cooling through radiation by the floor and mixing ventilation
6. Active cooling through radiation by the floor and displacement ventilation

\[ T_{\text{supply}} = T_a \]
\[ T_{\text{supply}} < T_a \]
\[ T_{\text{supply}} < T_a \]
\[ T_{\text{supply}} = T_a \]
\[ T_{\text{supply}} = T_a \]
\[ T_{\text{supply}} < T_a \]
Methods - Thermophysiological test room
Methods (2)

**Time schedule**

- **Acclimatization period**
  - Case S1
  - Case S2
- **Preparation**
  - $t=0$
  - 30
  - 60
  - 90
  - 120
  - 150
  - 180
  - 210
  - 240

**Measurements**

- Physical ($T_a$, RH, $v_a$, $T_r$, $E_v$) and physiological parameters ($T_{sk}$, $T_{cr}$, vasomotion) **continuously**.

**Questionnaires**

- Global and local comfort
- Remote Performance Method [*Toftum et al., 2005*]
Methods

Boundary conditions all cases:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{supply} = T_a</td>
<td>To = 24.5°C</td>
</tr>
<tr>
<td>T_{supply} &lt; T_a</td>
<td>To = 23.5°C</td>
</tr>
<tr>
<td>T_{supply} = T_a</td>
<td>To = 24.5°C</td>
</tr>
<tr>
<td>T_{supply} &lt; T_a</td>
<td>To = 23.5°C</td>
</tr>
</tbody>
</table>

PMV = 0 → T_a = T_{rm} (0.7 clo, 1.2 met)

10 healthy male subjects (♂)
10 healthy female subjects (♀)
Results - Males

\[ T_{\text{supply}} = T_a \]
\[ T_{\text{supply}} < T_a \]

\[ PMV = 0 \]
Results - Males

- $T_{\text{supply}} = T_a$
- $T_{\text{supply}} < T_a$

Graph: Thermal Comfort Whole Body

- 1. PC-C-M
- 2. AC-C-M
- 3. AC-C-D
- 4. AC-R-M-C
- 5. AC-R-M-F
- 6. AC-R-D-F

Percentage [%]

- Comfortable
- Slightly Comfortable
- Slightly Uncomfortable
- Uncomfortable
## Results - Males

### Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Norm</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Case 5</th>
<th>Case 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD Draft (DR) [%]</td>
<td>&lt;20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD Vertical air temperature difference [%]</td>
<td>&lt;5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD Warm or Cool floor [%]</td>
<td>&lt;10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD Warm or Cool Ceiling</td>
<td>&lt;5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results – Males vs Females

Passive cooling – Uniform (1)

\[ T_o = 25.3 \pm 0.17^\circ C \]
\[ T_a = 25.5 \pm 0.21^\circ C \]
\[ T_{rm} = 25.0 \pm 0.12^\circ C \]
\[ v_a = 0.27 \pm 0.02 \text{ m/s} \]

Active cooling – Non-uniform (4)

\[ T_o = 24.4 \pm 0.06^\circ C \]
\[ T_a = 24.1 \pm 0.08^\circ C \]
\[ T_{rm} = 24.6 \pm 0.04^\circ C \]
\[ v_a = 0.14 \pm 0.00 \text{ m/s} \]
Results – Males vs Females

\[ T_o = 25.3 \pm 0.17^\circ C \]
\[ T_a = 25.5 \pm 0.21^\circ C \]
\[ T_{rm} = 25.0 \pm 0.12^\circ C \]
\[ v_a = 0.27 \pm 0.02 \text{ m/s} \]

\[ T_o = 24.4 \pm 0.06^\circ C \]
\[ T_a = 24.1 \pm 0.08^\circ C \]
\[ T_{rm} = 24.6 \pm 0.04^\circ C \]
\[ v_a = 0.14 \pm 0.00 \text{ m/s} \]

Subject votes

<table>
<thead>
<tr>
<th>Variable</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMV [-]</td>
<td>0.3 ± 0.05</td>
<td>0.1 ± 0.07^</td>
</tr>
<tr>
<td>AMV [-]</td>
<td>-0.3 ± 0.64*</td>
<td>-0.4 ± 0.95*^</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Males</th>
<th>Females</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMV [-]</td>
<td>0.1 ± 0.02#</td>
<td>0.0 ± 0.02^,#</td>
</tr>
<tr>
<td>AMV [-]</td>
<td>-0.3 ± 0.41*</td>
<td>-0.6 ± 0.69*^</td>
</tr>
</tbody>
</table>

* Significant different from PMV (p<0.001)

^ Significant different from males (p<0.05)

# Significant different from case PC (p<0.001, within gender)
Results – Local skin temperatures

\[ T_{\text{supply}} = T_a \]

Males

\begin{array}{c}
\text{Local Tsk} \\
\text{Males Case PC}
\end{array}

Females

\begin{array}{c}
\text{Local Tsk} \\
\text{Females Case PC}
\end{array}

\[ T_{\text{supply}} = T_a \]

Males

\begin{array}{c}
\text{Local Tsk} \\
\text{Males Case AC}
\end{array}

Females

\begin{array}{c}
\text{Local Tsk} \\
\text{Females Case AC}
\end{array}
Results – Local thermal sensation

\[
T_{\text{supply}} = T_a
\]

\[
\text{AMV}_{;WB};\text{males} = -0.3 \pm 0.64
\]

\[
\text{AMV}_{;WB};\text{females} = -0.4 \pm 0.95
\]
Results – Subject votes

\[ T_{\text{supply}} = T_a \]

**Passive cooling - Uniform**

**Active cooling – Non-uniform**
Discussion

• Although cases were designed at PMV = 0, subjects thermal sensation votes significantly differed from neutral
  
  ➔ Is PMV (together with complimentary boundary conditions) applicable under non-uniform conditions?

• Uncovered body parts significantly influenced whole body TS
  
  ➔ Should focus be on extremities regarding the prediction of TS and TC?

• TS and TC between males and females were significant different
  
  • Males found active cooling more comfortable; females preferred passive cooling
  
  ➔ Emphasis should be on a more individualized assessment [Schellen et al. 2010]
Conclusion

- Operative temperature is not sufficient to assess TS and TC under non-uniform conditions

- Highly non-uniform environments can achieve a comparable or even a more comfortable assessment compared to uniform environments

- Under the studied uniform conditions the thermal sensation can be predicted well by the PMV model

- Contrary, non-uniform environments can achieve significantly different thermal sensation votes as predicted in advance

- The differences are most probably caused by local effects (local thermal sensations and local skin temperatures) and the presence of combined local discomfort factors.
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