INFLUENCE OF GENDER ON THERMAL SENSATION AND COMFORT IN INDOOR ENVIRONMENTS WITH DISPLACEMENT VENTILATION

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SUMMARY
This paper presents the results of a subject test study with regard to thermal sensation and comfort evaluation in the climate test bench “Aachen Comfort Cube” under displacement ventilation conditions for two mean temperatures of 20°C respectively 26°C. We investigated for both temperatures three vertical temperature stratifications of 1.0 K/m, 4.5 K/m and 10.0 K/m between the subject’s feet level (0.1 m height) and head level (1.1 m height). For each vertical temperature stratification at 20°C, respectively at 26°C 60 subjects participated. Both groups consist of male and female subgroups. For each setup, the subjects evaluated the local and overall thermal sensation and thermal comfort at 16 body parts with a questionnaire. We continuously measured the subject’s skin temperature at the following body parts: forehead, neck, back of the left hand, right scapula and right shin. Additionally, an infrared-camera measured the surface temperatures of the subjects and the test bench. Overall, this paper shows the correlation between skin temperatures and thermal sensation at the concerned body parts for the female and male subgroup and gives an outlook for further calibration approaches for a comfort model.

Keywords: displacement ventilation, thermal comfort, thermal sensation, Aachen Comfort Cube, thermal comfort modelling

1 INTRODUCTION
Providing high thermal comfort in indoor environments is one of the main objectives of air conditioning and ventilation systems. The concept of displacement ventilation is often used for cooling of indoor environments with low draft rate. To evaluate such systems in the design phase, a simulative approach can be used by a CFD-analysis coupled to a thermo-physiological human comfort model. However, those models have to be calibrated for a wide range of boundary conditions. Additionally, knowing the certain target groups for the subsequent application, an adaptation of the human model to those subgroups can provide results that are more sophisticated.

2 METHODS
We performed subject tests for six displacement ventilation setups with mean air temperatures of 20°C and 26°C and vertical air temperature stratification of 1 K/m, 4.5 K/m and 10 K/m) in the Aachen Comfort Cube (ACCu). The ACCu is a high modular climate test bench with a floor area of 2 m x 2 m and a height of 2.5 m. Each wall consists of four temperature-controlled surface elements over height. Additionally, the floor and the ceiling as well as the door and the front wall were also temperature controlled (Möhlenkamp et al. 2016).

For our tests, the supply air is induced symmetrically by air inlets at the bottom of the right and left wall of the test bench. The supply volume flow is 100 m³/h for each side, giving a total volume flow of 200 m³/h. The exhaust air leaves the ACCu through a circular opening in the ceiling. We controlled the...
vertical air stratification by the wall temperatures. To reduce the direct impact of radiation by the temperature-controlled walls on the subjects’ sensation, we implemented a sliced wall of white painted polystyrene. Thus, we assumed that wall temperature is nearly equal to the local air temperature (Möhlenkamp et al. 2016). We assessed air temperature with Pt100 temperature sensors at four vertical measurement lines at heights of 0.1 m, 0.6 m, 1.1 m and 1.7 m at the corners of the test bench. We defined the vertical temperature stratification between 0.1 m and 1.1 m, which nearly correspondents with the seated subjects feet level respectively their head level. The room mean temperature is defined as the mean air temperatures at 0.6 m height.

Figure 1 shows the test procedure. For each test run, three subjects participated. Before the test run started, the subjects were preconditioned in our climate-controlled test hall at 22°C for 30 minutes. Simultaneously, we equipped the subject’s skin with Pt100 temperature sensors at their forehead, neck, back of the left hand, right scapular and right shin. After the preconditioning phase, the subjects entered the ACCu and were seated on standard automotive seats. For one test run, we kept the mean air temperature constant and only varied the vertical temperature gradient. After 35 minutes adjustment for the 1 K/m setup we asked them to fill out a digital questionnaire regarding their thermal sensation and thermal comfort via tablet. After they completed the survey, we started the next setup with 4.5 K/m and the evaluation loop continued. The last setup with 10 K/m ended 135 min after the subjects entered the test bench.

![Figure 1. Test procedure](image)

For thermal sensation rating we used the German translation of the 7-point ASHRAE scale ranging from “cold” to “hot” (ASHRAE Standard 55; DIN EN ISO 7730). For thermal comfort we used the German translation of the a 6-point Berkeley-Comfort scale, ranging from “very uncomfortable” to “very comfortable” (Zhang 2003). For each setup we asked them to rate their overall sensation as well as local sensation at 16 body parts: head, chest, back, pelvis, left and right upper arm, left and right lower arm, left and right hand, left and right thighs, left and right lower legs, left and right foot. We also asked for some general questions to get information about the subject’s gender, age, weight, height and clothing. For clothing level determination we used standard clothing parts within the questionnaire (DIN EN ISO 7730; DIN EN ISO 9920). The subjects had free choice of adapting their clothing with regard to their preferences. After each evaluation, they had the chance to change their clothing, for example to take off a pullover. The subjects had to document every change in the questionnaire.

### 3 RESULTS

#### 3.1 Test panel distribution

For each mean air temperature, 60 subjects participated. For analysis of certain effects, we divided both groups into female and male subgroups, which are well balanced, see table 1.

<table>
<thead>
<tr>
<th>Mean air temperature</th>
<th>male</th>
<th>female</th>
<th>sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_m = 20^\circ C$</td>
<td>33</td>
<td>27</td>
<td>60</td>
</tr>
<tr>
<td>$T_m = 26^\circ C$</td>
<td>31</td>
<td>29</td>
<td>60</td>
</tr>
</tbody>
</table>
The boxplots in figure 2 show the properties of the four subgroups with regard to age, clothing, height and weight. Median of age is nearly equal for all subgroups. The most subjects are 20 to 40 years old; however, each subgroup contains some elderly people between 60 and 80 years, mostly marked as outliers. The male subgroup for the 26°C setups has bigger percentage of older people than the other subgroups, so that the elderly people are within the upper quartile respectively the upper whisker.

The calculated clothing values are shown for each mean temperature, because the change of clothing between the stratification setups within a mean temperature test run was marginal. We calculated the clothing values for the subgroups without the seat. For consideration of an automotive seat, DIN EN ISO 9920 proposes to add 0.25 clo. The boxplot shows, that general clothing level distribution is slightly different between male and female subgroup for 20°C mean air temperature. The female subjects preferred slightly warmer clothing combinations than the male. For the 26°C setups those difference is not present. A comparison of the subgroups for both mean temperatures show, that for the cooler setups a fraction of the subjects used to wear warmer clothing than for the warmer 26°C setups.

Results for height and weight of the subgroups show, that for both mean air temperatures there are only differences for gender observable. The persons in the female subject group are smaller and lighter than the male subjects.

### 3.2 Skin temperature measurement

Figure 3 shows mean value distribution of the skin temperature measurements for the evaluation phases at the subject’s forehead and their neck. The forehead temperature data for each stratification setup are nearly equal for both gender subgroups. With rising stratification gradient respectively rising air temperature at head level of the subjects, the forehead temperature rises, too. Additionally, an offset between both mean air temperatures is observable.

The neck temperature data show differences between the male and female subjects for 20°C mean air temperature. The median of the female subjects is more than 2 K warmer than for the male subjects. For 26°C mean air temperature, this effect is marginal, but still approximately 1 K for stratifications of
1 K/m and 4.5 K/m. For all subjects the neck temperature increases with rising vertical temperature stratification.

Figure 3. Measured skin temperatures at forehead (20°C: up left; 26°C: up right) and neck (20°C: low left; 26°C: low right)

3.3 Thermal sensation and thermal comfort

Figure 4. Overall Thermal Sensation: 20°C (left) and 26°C (right)

Figure 5. Overall Thermal Comfort: 20°C (left) and 26°C (right)

The evaluation of thermal sensation is shown in figure 4. The subjects’ ratings reach from cool to slightly warm for the setups with a mean air temperature of 20°C, whereas they reach from neutral to
warm and for higher vertical gradients to hot for setups with a mean air temperature of 26°C. For the 20°C setups we could assess a slight difference in the results depending on the gender. The median is neutral for the male subjects and slightly cool for the female subjects. For the warmer setups of 26°C, the median is equal for both gender subgroups.

Figure 5 shows the results for overall thermal comfort evaluation. The median of the ratings varies between just comfortable to just uncomfortable. By tendency, the male subjects rate the 20°C setup more comfortable than the female subjects do. For the warmer 26°C setups, the female subjects’ evaluation is slightly more comfortable than the males’ evaluation. Especially, for the setups with stratifications of 1 K/m and 4.5 K/m the median is just comfortable for the female subjects and just uncomfortable for the male subjects. Some female subjects rate the setup with 10 K/m at 26°C as very comfortable, whereas the best voting of the male subject group is comfortable. However, the median is just uncomfortable for both gender subgroups.

3.3 Correlation between thermal sensation and skin temperature

Figure 6 shows the correlation between the overall thermal sensation and the forehead skin temperature depending on the gender. Both diagrams show that the thermal sensation rating increases to the warmth with rising measured skin temperature. The median forehead skin temperature for a neutral thermal sensation is 1 K higher for the female subjects than for the male subjects.

![Figure 6. Correlation between forehead skin temperature and overall thermal sensation.](image)

For both plots, we added a linear regression line. This leads to the equations (1) and (2) for overall thermal sensation for male and female subjects. The slope is nearly equal for both functions, whereas the axis intercept is ~0.5 scale units higher for the male subjects.

\[
\begin{align*}
TS_{\text{Overall,male}} &= \frac{1.364}{^\circ \text{C}} \cdot T_{\text{forehead}} - 40.871 \\
TS_{\text{Overall,female}} &= \frac{1.366}{^\circ \text{C}} \cdot T_{\text{forehead}} - 40.355
\end{align*}
\]

4 DISCUSSION

For equal environmental conditions, we see a different physiological response depending on gender for certain body parts like neck. For other body parts like the forehead, the tests we performed did not show a difference for female and male subjects. When talking about gender differences, we have to keep in mind that physiological factors as height and weight significantly differ for both considered subgroups. Clothing insulation also has an influence on thermal sensation. However, the subjects were invited to dress with their individual preferences and furthermore had the opportunity to adapt their clothing during the tests. The difference in data distribution of mean neck temperature for a mean air temperature of 20°C correlates with the higher clothing values of the female subjects. However, a small temperature difference between the subgroups is still observable for a mean air temperature 26°C and nearly equal clothing values. In contrast to that, the evaluation of thermal sensation is slightly shifted to the cool for the female subjects for setups with 20°C. Many authors who performed similar studies also described
the effect that differences in evaluation of thermal sensation between women and men occur for cool environments (Webb and Parsons 1997; Parsons 2002; Karjalainen 2012).

5 CONCLUSIONS AND OUTLOOK

We can confirm results from literature which show that female subjects rate cool environments more uncomfortable compared to male subjects. Moreover, male subjects rate warm environments slightly more uncomfortable than women. However, these are first conclusions from this data set and a more detailed analysis is required. For the development and tuning of thermal comfort models, the knowledge of the relation between physiological signals and perception of subjects is crucial. Consequently, correlations between skin and core temperature data and evaluation of thermal sensation and comfort are required. The presented study shows a good correlation between forehead temperature and overall thermal sensation. We found slight differences in the transfer function for male and female subgroups. To understand the whole interactions and driving factors, other body parts have to be analysed in detail with regard to local skin temperature measurements and subjective evaluation. Further test data of skin temperatures at left hand, right scapular and right shin as well as the local evaluations are available, but not evaluated yet. Especially, the effects at upper and lower body parts have to be considered for the investigated displacement ventilation concept. Additionally, suitable statistical test methods as the Wilcoxon-Rank-Sum-Test have to be used for determination of significance and effect size.

REFERENCES


