Human response to thermal environment in rooms with chilled beams

Arsen Melikov¹, Boryana Yordanova¹, Lyuben Bozkhov¹, Viktor Zboril¹,², Risto Kosonen³

¹International Center for Indoor Environment and Energy, Department of mechanical
Engineering, Technical University of Denmark
²Department of Environmental Engineering, Faculty of Mechanical Engineering, CTU in
Prague, Prague 166 47 - Czech Republic
³Halton Oy

Corresponding email: melikov@mek.dtu.dk

SUMMARY

The importance of heat load and airflow pattern control for occupants’ thermal comfort is
studied in a full-scale test room ventilated with chilled beams. The room was furnished with
two desks, computers and table lights. Solar irradiation on window and part of the floor was
simulated as well. The room temperature was maintained at 24ºC. Thirty subjects (15 female
and 15 male subjects) participated in the experiments. The increase of the heat load from 30
W/m² to 70W/m² increased substantially non-uniformity of the thermal environment in the
room. The percent of subjects dissatisfied due to their thermal comfort conditions and due to
draught increased with the increase of the heat load. The provided induction control of the
chilled beams changed the air flow distribution in the occupied zone and decreased the
reported draught discomfort. The induction control is efficient way for improving occupants’
thermal comfort but it should be used carefully in practice.

INTRODUCTION

The air-conditioning of office buildings is maintained mainly with systems based on the mixing
ventilation principle. During the recent years the use of active chilled beams for ventilation of
buildings has increased due to their ability for removing higher heat loads in more energy
efficient way than other systems for office ventilation [1]. Furthermore chilled beams, allow for
control of the induced amount of room air and thus for change of airflow pattern in rooms when
uncomfortably high velocity is reported by occupants.

Air distribution in rooms with active chilled beams is result of complex interaction of
ventilation flow from the beams with the convection flow generated by heat sources, occupants,
warm/cold window surfaces, office equipment. The airflow distribution depends on several
factors, including arrangement of chilled beams, supplied airflow rate and momentum flux, lay
out of workplaces, strength and location of heat sources, etc. Only limited studies on the air
distribution in rooms with chilled beams is reported in the literature [2, 3, 4]. The impact of the
airflow interaction in rooms with active chilled beams on occupants’ comfort is needed. The
efficiency of the airflow pattern control for achieving comfortable thermal conditions for
occupants is not documented.

This paper presents results on human response to thermal environment generated by active
chilled beams. The impact of heat load and airflow pattern control on thermal comfort is
studied with human subjects under realistically simulated laboratory conditions. Only part of the collected and analyzed results are presented and discussed in this paper.

**EXPERIMENTAL DESIGN**

**Experimental facilities**

A full-scale test room ($L \times W \times H = 5.4m \times 4.2m \times 2.5m$) was used to simulate a real office room. The room was furnished with two desks each with a real computer to simulate the heat loads from office equipment. Artificial windows with surface temperature control were used to simulate the impact of the outdoor environment during summer season. Several heating panels were placed on the floor and used in some of the experiments to generate heat and simulate solar irradiation (it is difficult to simulate properly the solar radiation). The work place near the window is referred as WP2 and this on the opposite side as WP1 (Figure 1).

Three chilled beams were mounted crosswise installation as shown in Figure 1. Previous physical measurements identified this lay out as most critical in regard to occupants’ thermal comfort [3]. The amount of room air inducted into the beams was regulated by shutters placed in the beams. When the shutter is closed (right side of the chilled beam shown in Figure 1) maximum cross section area for the flow is ensured and thus maximum amount of room air is induced through the beam). This setting is referred in this paper as “Induction 1 (I1)”. When the shutter is open (left side of the chilled beam in Figure 1) the cross section area decreases and thus the air supplied to the room decreases (the amount of induced room air also decreases). This setting is referred as “Induction 2 (I2)”.

The surface temperature of the artificial windows, the air temperature, etc. were measured and controlled.

**Experimental conditions**

Three experiments referred in Table 1 as Case 1, Case 2 and Case 3 were performed. In cases 1 and 2 the heat load was kept constant but the induction of room air was changed, Induction 1 (I1) and induction 2 (I2). The low induction (Case 2) was activated for the side of the chilled beams facing WP1. The cooling capacity of the chilled beams was maintained the same by lowering of the temperature of the inlet water for the heat exchanger. In Cases 1 and 3 the induction was kept constant (I1) but the heat load was changed.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Induction control</th>
<th>Temperature in the room, °C</th>
<th>Heat loads, W/m²</th>
<th>Surface temperature of windows, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>High induction (induction 1)</td>
<td>24.0± 0.2</td>
<td>70</td>
<td>40.4</td>
</tr>
<tr>
<td>Case 2</td>
<td>Low induction (induction 2)</td>
<td>24.1 ± 0.1</td>
<td>70</td>
<td>41.5</td>
</tr>
<tr>
<td>Case 3</td>
<td>High induction (induction 1)</td>
<td>24.0 ± 0.2</td>
<td>30</td>
<td>36.1</td>
</tr>
</tbody>
</table>
Figure 1. Experimental set-up in the room and sketch of cross section of the chilled beam with right shutter closed and the left shutter open is shown as example.

During the experiments the flow rate of the primary air was 1.5l/s/m². The experiments represented summer conditions and the room temperature was maintained to be 24ºC.

The distribution of the heat loads in the test room for each case is listed in Table 2. The window surface temperature of 40.4 ºC is high but possible in practice.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Heat gain from windows, W</th>
<th>Heat gain from PCs, W</th>
<th>Heat gain from people, W</th>
<th>Heat gains from floor panels, W</th>
<th>Heat gain from lightning, W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>2x325</td>
<td>2x80</td>
<td>2x75</td>
<td>520</td>
<td>116</td>
</tr>
<tr>
<td>Case2</td>
<td>2x325</td>
<td>2x80</td>
<td>2x75</td>
<td>520</td>
<td>116</td>
</tr>
<tr>
<td>Case3</td>
<td>2x220</td>
<td>-</td>
<td>2x75</td>
<td>-</td>
<td>116</td>
</tr>
</tbody>
</table>

**Subjects**

Thirty subjects, 15 males and 15 females, participated in the experiment. They were at age from 20 to 45 years (average 24.3 ± 5 years).

**Experimental procedure**

Each subject participated in three experiments (Cases 1, 2 and 3 in Table 1). At their arrival, before entering the experimental office, the subjects relax for 20 minutes from previous activities. During that time they were explained the experimental procedure and how to fill in
the questionnaires. They were not informed about the experimental conditions, e.g. the temperature in the room, the ventilation system, the flow rate, etc. After 20 minutes the subjects entered the test room two at a time and sat at the workplaces. They were asked to fill in the questionnaires every 5 minutes staring from the fifth minute. The subjects were allowed to write or read while seated on the desk. The subjects stayed in the office 25 minutes then they went out for 10 minutes break. After the break they returned to the office and stayed there for another 25 min. This time they changed the workplaces. They completed questionnaires as during the first 25 min. During the whole experiment the subjects were encouraged to adjust their clothing according to their preferences. At the end of the experiment for the day they filled in a questionnaire about their clothing. This procedure was identical for the three experiments the subjects participated.

**Questionnaires**

The subjective response to the thermal environment was collected by means of questionnaires. They were presented to the subjects on a paper. The questions related to whole body and local thermal sensation - 7-point ASHRAE scale [6], acceptability of the thermal environment (ranging from clearly unacceptable to just unacceptable and then from just acceptable to clearly acceptable, air movement sensation, body part where the movement was felt, whether it was acceptable or not, and the last question was on preference for more, less or unchanged air movement.

**Data analyses**

The data obtained from the questionnaires was analyzed statistically using the program Statistica 5. Each of the samples was tested for normality of the distribution using the Shapiro-Wilk test. Tests for significant differences of the samples were performed with Wilcoxon match pair test.

**RESULTS AND DISCUSSION**

The individual whole-body thermal sensation votes as reported by the subjects were used to define the average thermal sensation vote. Figure 2 compares the obtained results for each of the three experiments. The average thermal sensation of the occupants in all of the cases was within the comfortable range of ±0.5 (from slightly cool to slightly warm) recommended in the present standards [6, 7]. Only at WP2 in Case 2-70W/m²- I2 the thermal sensation was above slightly warm, 0.7. In this case the thermal sensation of the occupants was influenced by the thermal radiation from the warm windows which were located 0.9 m from WP2. The thermal sensation was just below neutral only at WP1 in the experiment with 30W/m² (Case 3).

The results were statistically checked for significance. Significant differences were found in the average thermal sensation between WP1 and WP2 in Case 2-70W/m²- I2 (p=0.006), at WP2 between Case 1- 70W/m²-I1 and Case 2- 70W/m²-I2 (p=0.0262) and at WP2 between Case1-70W/m²-I1 and Case3-30W/m² (p=0.039). The subjects felt warmer the whole body with the conditions at WP2 in Case 2-70W/m²- I2.

The local thermal sensation for the different body parts as reported by the subjects was analyzed. The local thermal discomfort due to warmth was defined for the body parts with
local thermal sensation “slightly warm”, “warm” or “hot” which was felt as uncomfortable. Figure 3 shows the results of these analyses.

Figure 2. Average thermal sensation of the subjects at workplace 1 (WP1) and workplace 2 (WP2).

Figure 3. Percent dissatisfied due to warmer body parts

The highest percent of subjects who felt local warm discomfort for one or more body parts was for Case 2 -70W/m²- I2. The conditions at WP2 in Case 2 -70W/m²- I2 were identified as the worst; almost half of the assessment panel (43%) felt discomfort at that workplace located close to the heated window. The local warmth discomfort decreased when the heat load in the room decreased (Case 3- 30W/m²).

During the experiments the subjects were asked to assess whether they felt air movement at any of the specified body parts and if so, if the air movement was comfortable or not. The subjects’ responses were defined as draught discomfort if: 1) the person felt particular body part cooler than neutral and 2) if the person felt the local cooling uncomfortable; and 3) if the
person felt air movement and voted that the feeling is uncomfortable and 4) the subject requested for “less air movement”. Figure 4 represents percentage dissatisfied due to draught at any body part.

![Figure 4. Percent dissatisfied due to draught based on all four criteria](image)

The highest percent of subjects who felt draught was reported in Case 1 - 70W/m²- I1 at WP1. When the induction control was used, Case 2-70W/m²-I2, the percent dissatisfied due to draught subjects at WP1 was lowered substantially; in this case only one person reported on draught. The results show that with the lowering of the strength of the heat sources (Case 3 - 30W/m²) the total percent of draught complaints decreased.

**DISCUSSION**

Acceptable thermal environment for the whole body was achieved under all the tested conditions. The average thermal sensation of the subjects achieved with the chilled beams at the two workplaces was between neutral and slightly warm. As expected due to the radiant temperature asymmetry generated by the warm window the subjects felt warmer at the WP2 than at WP1. The flow interaction as discussed in the following left the subjects at WP2 with less air movement for cooling their body. However this did not affect subjects’ general thermal sensation.

The general thermal sensation, the local thermal sensation and the draught discomfort reported by the subjects was result of the interaction of the thermal flows generated by heat sources and the ventilation flow supplied from the chilled beams. The convection flows from the window, the solar irradiation simulated on the floor, the person and the PC concentrated on one side of the window (WP2) in Case 1 (70W/m²- I1) were powerful enough to deflect the ventilation flow toward the opposite side of the room as shown schematically on Figure 5. This resulted in large number of draught complains at WP1 (Figure 4). The use the induction control of the chilled beams on the side of the WP1 (Case 2-70W/m²-I2), decreased the velocity which resulted in decreased draught complaints at WP1 as well as at WP2. The local thermal discomfort decreased as well (Figure 3). Thus the efficient use of the induction control for decrease of draught discomfort in rooms with chilled beams was validated.
The activated induction control decreased the draught complaints but the number of subjects reporting warmth discomfort at WP2 increased from 10 to 13, i.e. near the window. Due to the airflow interaction less cooling air reached the subjects at WP2 and this resulted in warmer thermal sensation. Thus the warmth discomfort should be carefully considered together with draught discomfort in practice in rooms with chilled beams when induction control is provided.

Figure 5. Air distribution in Case 1 (70W/m² - I2)

The importance of the airflow interaction was demonstrated in the experiments with different heat load as well. Non-uniformity of the thermal environment decreased when the heat load was decreased from 70W/m² (Case 1) to 30W/m² (Case 3) and this affected occupants’ thermal comfort. Draught discomfort decreased (Figure 4), the whole body thermal sensation improved (Figure 2) and the reports on uncomfortable local warmth discomfort decreased (Figure 3).

The results reported in this paper were supported by results from comprehensive physical measurements on air distribution and thermal environment in rooms with chilled beams [3, 4]. They confirm the importance of careful consideration of flow interaction in rooms in general. In future buildings occupants and solar irradiation will remain the major heat sources. The increase of the outdoor temperature due to global warming and the use of glass facades will affect the airflow interaction in spaces resulting in increased non-uniformity of the thermal environment. At the same time the recognized impact of the indoor environment on occupants’ performance [9] will lead to requirements for higher quality of indoor environment in the future standards than the requirements specified in the present indoor climate standards. Therefore the need for of individually controlled environment in buildings which will be able to compensate for the non-uniformity of the indoor environment and for the large individual differences existing between people in regard to the preferred environment will increase.

CONCLUSIONS

For the conditions provided by the chilled beams the average thermal sensation of the subjects was within the requirements of the existing standards and guidelines (ISO 7730, CEN 1752, REHVA Guidebook).
The flow interaction in the room under the studied conditions had major impact of occupants draught sensation. Higher draught discomfort was discovered for the conditions with higher heat load in the room. The induction control proved to be efficient way for diminishing draught discomfort.

ACKNOWLEDGEMENT

This research was supported by the Danish Technical Research Council (STVF) and the Finnish Technology Agency (TEKES).

REFERENCES