Air Distribution in Rooms, (ROOMVENT 2000)
Editor: H.B. Awbi

13375

A NOTE ON THE THERMAL COMFORT IN DISPLACEMENT VENTILATED CLASSROOMS

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ABSTRACT

19 university students were asked about their thermal comfort while attending ordinary lessons in a displacement ventilated test room of typical classroom size. Two different ceiling heights were tested. Both the general temperature level and the strength of the vertical temperature stratification in the room increased continuously during the lessons due to the presence of the students, however slower with the higher ceiling. The temperature stratification of the air eventually reached a strength of 3.1°C/m, which, according to international standards, should cause some complaints about the thermal comfort. There was however no indication of that the students could feel this stratification. The fact that the vertical *radiative* temperature asymmetry was comparatively small in the room – due to radiative heat exchange between the interior surfaces – is believed to be a major reason for this insensitivity of the students to the vertical air temperature stratification.

KEYWORDS

Thermal comfort, displacement ventilation, temperature stratification, temperature gradient, non-steady state, classroom, densely populated rooms, ceiling height.

INTRODUCTION

The air in displacement ventilated rooms will always be more or less temperature stratified. Some previous studies – in particular that by Olesen et al (1979) – have indicated that a too strong stratification will cause thermal discomfort, although the mean temperature in the room is at a comfortable level. This has led to recommendations on the maximum temperature stratification in two international standards: ISO 7730 (1994), recommending less than 3.0°C air temperature difference between 0.1 m and 1.1 m above floor (= $T_{1.1\text{-}0.1}$), and the ANSI/ASHRAE standard 55 (1992), recommending less than 3.0°C air temperature difference between 0.1 m and 1.7 m (= $T_{1.7\text{-}0.1}$). These recommendations have however been questioned, e.g. by Wyon & Sandberg (1996) who found no significant impact on the thermal comfort of test persons, even when these were exposed to a stratification of 4°C/m.

The studies and recommendations mentioned above concern steady-state conditions. In this study, university students were asked about their thermal comfort in connection with ordinary lessons, during which the temperature continuously was rising due to the presence of the students. Two different ceiling heights of the classroom were tested, giving different development of the temperature rise.

METHOD

The study was performed in a test room of normal classroom size; see Figure 1. The main objective of the study concerned the efficiency of the ventilation system from an air quality point of view; in particular how this efficiency is influenced by the activity of people (see Mattsson 1999). The opportunity was however taken also to ask the test persons about their thermal comfort during the experiments. The ceiling of the classroom was vertically adjustable, and the ceiling height was fixed at 3.0 m in the first test (performed in mid September, in the morning) and at 4.2 m in the second test (performed in mid

November, also in the morning). The median age of the 19 participating students was 26 years (1^{st} quartile: 24 years, 3^{rd} quartile: 31 years); three of them were women. The same students, except two of them, took part in both of the tests, and they were seated on the same places in the classroom.

The classroom was well insulated: 195 mm mineral wool between two 12 mm particle boards (38 mm board on the floor), hence making up a construction of low thermal mass. The classroom was situated in a lab hall, in which a temperature of 21.5±0.5°C was maintained. The doors to the outdoor climate simulation room were open towards the lab hall in order to attain the same temperature around the whole classroom. Two cylindrical displacement diffusers (effective outlet area: 0.056 m^2 each) supplied air at totally 191 litres/s. The same amount of air was extracted by two terminals located as in Figure 1, in contact with the ceiling. The supply air temperature was kept constant at 20.6°C when the ceiling height was 3.0 m, and at 20.3°C when it was 4.2 m. This level of the supply air temperature was chosen since some previous tests in the classroom had indicated that a roughly 4°C temperature increase was to be expected in the occupied zone during the tests, and since the rough guidelines given in ISO 7730 (1994, Appendix A.1.1) suggest an operative temperature of 20-24°C during the heating period of the year (at light, mainly sedentary activity). The ventilation was left running – with no heat sources activated in the room – during 24 h before the start of the tests, thus ensuring steady starting conditions. Air temperatures at different heights in the room were recorded using 0.5 mm thermocouples, mounted in the position marked in Figure 1. The thermocouples were calibrated prior to the experiment, giving an absolute uncertainty of ±0.1°C.

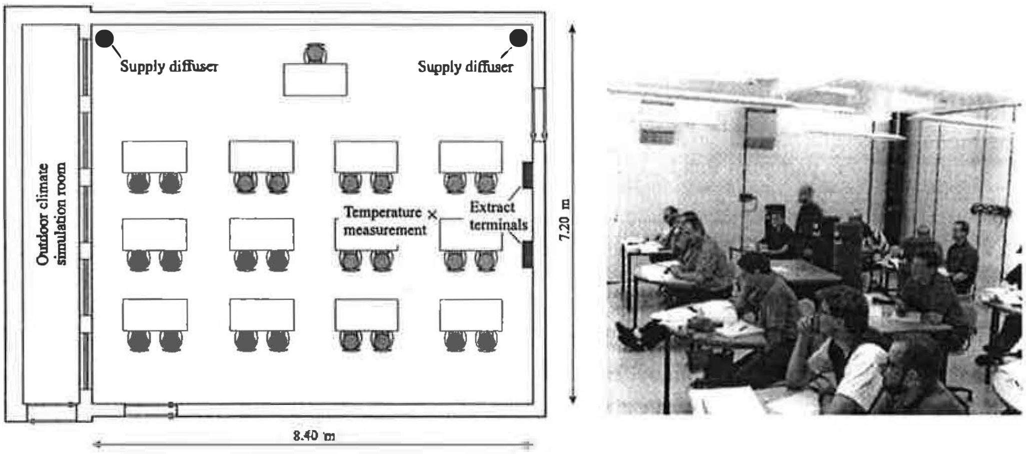

Figure 1: Set-up (to scale) of the classroom and a picture taken when the ceiling height was 3.0 m.

At the start of the tests, the ceiling lighting (525 W) was switched on and all students entered the classroom at once. The students were seated two and two according to Figure 1. On five of the seats in the mid row, electrically heated (95 W) person simulators were seated instead of students. (These person simulators were needed for comparison with other tests, described by Mattsson 1999). At each test, two 90-min lessons were given, with a 22-min break in between, during which the students left the room. A teacher (not involved in the survey) was giving a lecture during both lessons. During the first lesson, the students were asked to walk around in the room for ~65 s, once every 20 min (in order to see the impact on the ventilation efficiency); the last walk was thus executed after 80 min. The students remained seated throughout the second lesson.

At the end of each of the lessons (after about 87 min), the students were handed a questionnaire, asking about their thermal comfort. The students were asked to state their *local* thermal comfort for six different parts of the body, as well as their *general* thermal comfort. Besides stating their momentary comfort, they were asked to recall how they felt at the beginning (after ~5 min) and in the middle (after ~45 min) of the lessons. The main reason for not letting them make these assessments in "real time" during the lessons was not to disturb their lessons more than already done. It was reasoned that there was a good chance that the students could remember and state how they felt on the rather crude three-level scale:

"Unpleasantly cold" – "Good or Acceptable" – "Unpleasantly warm".

The students were told beforehand that the experiments concerned the air quality in the room, but nothing was said about the thermal comfort study. Further, no clothing instructions/recommendations were given, but the students were expected to show up dressed as they would at an ordinary school day. In the questionnaire, the students were also asked to describe their clothing. More details of the experimental conditions are given by Mattsson (1999).

RESULTS

Figure 2 shows the development of the temperatures in the classroom. Apparently, the temperature kept rising during both lessons, and also the temperature stratification in the occupied zone became stronger. The temperature peaks occurring at the 0.1-m level every 20 min during the first lesson are caused by the walking exercises of the students, and the big peaks at the end of the lessons are due to mixing of the room air by mixing fans (for air quality measurements). The lowest and the uppermost temperature indication in the right graph represent the surface temperature of the floor and of the ceiling, respectively.

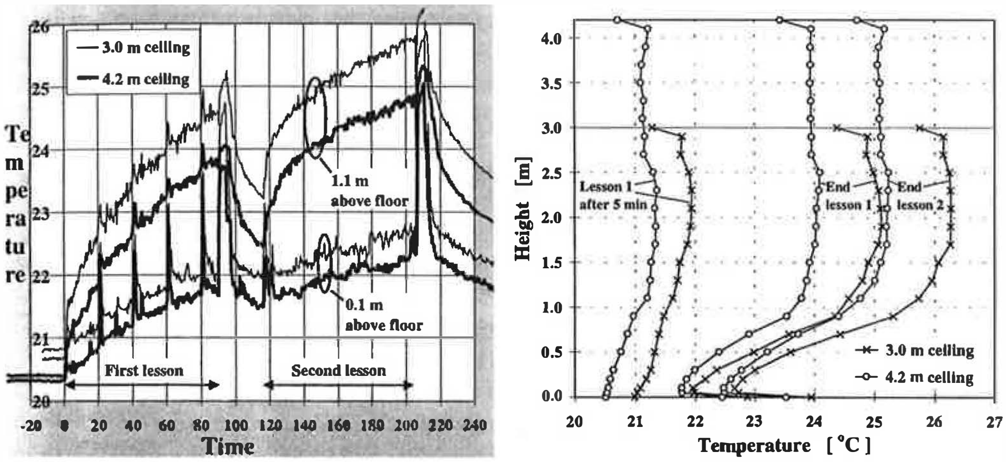

Figure 2: Series of air temperatures at 0.1 m and 1.1 m above floor (left), and temporal development of vertical air temperature profiles (right). ("End of lesson" = after 88 min.)

In can be seen that the initial room temperature was almost 0.5°C lower in the 4.2-m ceiling case; this is due to the slightly lower supply air temperature and the fact that also the lab hall temperature then was about 0.5°C lower. This difference in starting conditions was unintentional. It is clear in the right graph that the air temperature mainly is stratified in the lower, occupied zone of the room, whereas it is fairly uniform in the upper zone. It also appears that the lower, stratified zone extends to about the same height for both ceiling heights. One can further note that the temperatures rise slower with the higher ceiling, most likely due to the greater mass (walls + air) that then exists to heat.

Table 1 lists the critical air temperature differences $T_{1.1-0.1}$ and $T_{1.7-0.1}$. It is seen that the recommended limit of the standards mentioned above (3°C) is reached, and even exceeded, at the end of the lessons with 3.0 m ceiling. The relative humidity of the room air stayed between 30-40% during both tests.

Figure 3 shows how the general thermal comfort was assessed for the two lessons for both ceiling heights. According to the figure, no student ever felt too cold, but during each lesson more and more felt too warm. Treating the data for each lesson separately, and having stated *á priori* that the trend of increasing "unpleasantly warm"-scores was expected, the nonparametric Page's L-test for ordered alternatives (see e.g. Siegel & Castellan, 1988) was used to test the significance of the trend. The trends for all lessons, except lesson 1 in the 4.2m-ceiling case, then proved significant ($p<.05$). That is, there is little doubt that the students could feel the temperature rising. In keeping with the recorded temperature variations – Figure 2 – they also complained less about warm temperature when the ceiling was higher.

Table 1. Vertical air temperature differences: $T_{1.1-0.1}$ | $T_{1.7-0.1}$ [°C].

	Beginning of first lesson	End of first lesson	End of second lesson
3.0 m ceiling	0.6 | 0.8	2.6 | 3.1	3.1 | 3.6
4.2 m ceiling	0.7 | 0.8	2.0 | 2.2	2.3 | 2.8

From the clothing description given by the students, their clothing insulation could be estimated, using for instance Table 4 in ISO 7730 (1994). This indicated a mean clothing insulation of 0.73±0.11 clo at the first test (3.0-m ceiling), and 0.95±0.13 clo at the second test (4.2-m ceiling). The students thus wore more clothes at the later test ($p<0.01$), which was held during a colder time of the year. No correlation was however found (at either of the tests) between clothing insulation and stated general thermal comfort; i.e. well insulated students did not declare themselves to be warmer than the less insulated did.

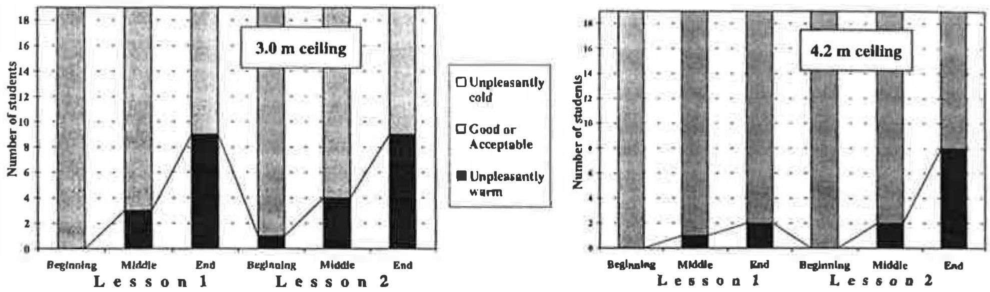

Figure 3: General thermal comfort as stated by the students for the two different ceiling heights.

Table 2.

	Height above floor [m]
Feet	0.05
Calves	0.25
Thighs	0.50
Trunk	0.75
Hands	0.75
Arms	0.80
Head	1.15

Table 3.

"Unpleasantly cold"	- 1
"Good or Acceptable"	0
"Unpleasantly warm"	+ 1

In order to construct a measure of sensed temperature stratification, the six assessed body parts were assigned a value representing their approximate mean height over the floor surface, according to Table 2. Further, the three comfort levels were assigned the values according to Table 3. For each student, a least-squares regression line was then fitted to the student's local-comfort data, giving comfort-score as a function of body-part height. The *slope* of that line was then taken as a *measure of the sensed vertical temperature stratification*. A positive slope thus indicates that upper body-parts feel warmer than lower parts. Two examples for clarification: If the three lowest body-parts are assigned the value 0, and the upper parts the value +1, the slope becomes +1.24; if the 0-values of the lowest parts instead are exchanged for −1, the slope reaches its highest value: +2.48. Corresponding negative slopes arise if the signs of the scores are shifted; that is, if the upper body-parts feel colder than the lower parts.

Figure 4 shows the frequency distribution of the comfort-slope values, calculated from the scorings of the students at the end of lesson 1 and lesson 2 for the 3.0m-ceiling case. At these two occasions the strongest temperature stratifications were recorded, and the students were making their scoring while they were exposed (i.e. no retrospective scoring). There is a striking collection of slope values around zero; most of these were exactly zero due to same scoring being given for all body-parts, but some of them were zero due to both head and feet being reported warm while the middle part of the body being reported neutral. It is then interesting to see that slope-values differing from zero are about equally distributed on either side – there are just as many students reporting that they feel a positive stratification as there are reporting a negative stratification. The mean values of the slopes, 0.032 and 0.036 respectively (with standard deviations 0.48 and 0.46 respectively) differ insignificantly from zero. The slope-distributions for the 4.2 m ceiling case and at other times were similar to those in Figure 4, but with less deviations from zero (neutral). Students sitting in the front line, closest to the inlet terminals, were in fact exposed to a slightly stronger stratification than the others, but they were not overrepresented in the "positive stratification"-group. Thus, according to this "comfort slope"-method, the students could not feel that the air temperature was increasing with height in the room; not even at the end of lesson 2, when $T_{1.1-0.1}$ and $T_{1.7-0.1}$ slightly exceed the recommendations in the standards, as was noted in Table 1.

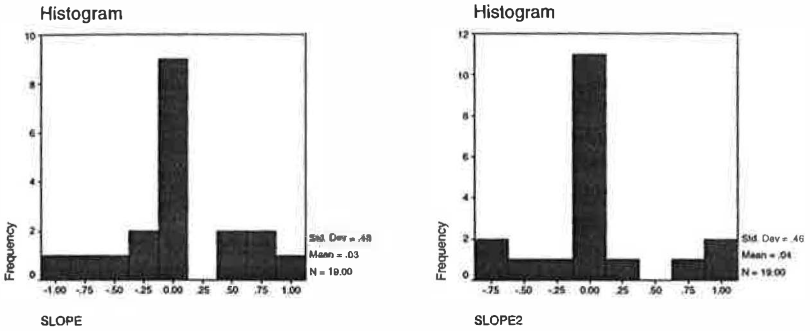

Figure 4: Frequency distributions of the perceived temperature stratification (= "slope") at the end of lesson 1 (left) and at the end of lesson 2 (right) when the ceiling height was 3.0 m.

DISCUSSION AND CONCLUSIONS

Regarding the general thermal comfort, unexpectedly many students found the temperature unpleasantly high at the end of the lessons. Assuming an activity level of 1.2 met (light, mainly seated activity) and applying the mean values of the clothing insulation of the students, the temperature graph in ISO 7730 (1994, Fig. 2) indicates an optimal operative temperature of about 23.5°C for the 3.0-m ceiling case and 22.5°C for the 4.2-m ceiling case. A deviation of maximum 2°C from these values is stated to keep the number of dissatisfied occupants below 10%. When trying to form an operative temperature from Figure 2 it would seem that, at the end of lesson 2, this temperature was higher than the optimal values, but still within the 2°C-limit. The circumstance that the number of dissatisfied students then was as high as 47% and 42% respectively (Figure 3) hence seems inconsistent with the ISO 7730 standard. Further, the fact that it takes some time for a human body to adapt to a temperature change suggests a dampened response of the students to the continuously rising temperature. However, the close presence of the warm body of a neighbour at the table will raise the operative temperature sensed by the students; perhaps this could be one explanation to the unexpectedly many "unpleasantly warm"-scores. Another explanation might lie in the very low air velocities that normally exist in displacement ventilated rooms (except close to floor), having a hampering effect on the convective part of the heat loss. The ANSI/ASHRAE standard 55 (1992, Fig. 1) suggests somewhat lower optimal temperature ranges: about 22.9±1.7°C (3.0 m ceiling) and 21.6±1.7°C (4.2 m ceiling), which are in better agreement with the present data than ISO 7730, but still appear to over-predict the optimal temperature somewhat.

A more intriguing finding was the absence of any indication of that the students could feel the temperature stratification of the room air, despite this stratification reached – and even slightly exceeded – the upper limits given in the standards (Table 1 & Figure 4). One plausible reason for this insensibility could be the fact that students practically always wear outdoor footwear inside the school; at least in Sweden. The shoes worn outdoors in September/November in middle Sweden are often fairly robust. Checking the clothing listing given by the students revealed that at the 3.0-m ceiling case, to which Figure 4 applies, one student wore real boots, while the rest of the students wore "ordinary" (one-layer) walking shoes or gym shoes; i.e. not *very* warm footwear. In the experiments by Olesen et al. (1979), however, the test persons wore sandals, making these persons more sensitive to cool air at the feet. In addition, the ISO 7730 standard states that the risk of draught is lower when people are feeling too warm, which is the case here; this helps explaining the absence of reported cold feet. Further, as stated above, a certain time-delay in comfort reaction is expected in transient cases like the present; stronger reactions to the temperature stratification might have occurred if the exposure had been longer.

Another, perhaps more weighty explanation to the inability of the students to sense the temperature stratification relates to the radiative heat exchange between the indoor surfaces. This heat exchange makes the spatial variation of the surface temperatures smaller than that of the air. That is, the *radiative* temperature "stratification" becomes weaker than the "convective" stratification. This can clearly be seen in Figure 2, where the temperature of the floor surface is considerably higher than that of the adjacent air, and the surface temperature of the ceiling is lower than that of the air below it. The appearance of these temperature differences between surfaces and the ambient air is typical of displacement ventilated rooms, and it will ease the sensed temperature stratification. In the test room used by Olesen et al. (1979), the upper surfaces were heated and the lower surfaces cooled in order to create the desired temperature stratification of the room air. These surfaces were further covered with aluminium foil in order to reduce the radiant emission. This artificial arrangement differs thus from the conditions in real displacement ventilated rooms, and it seems possible that it implies a stronger radiant asymmetry than appears in reality. This calls for caution when applying the results by Olesen et al. to real cases.

The finding that students wearing more clothes did not feel warmer than the others might be due to the individual clothing being dependent on the personal temperature sensitivity. That is, people that tend to feel colder than others wear more clothes; hence the reaction to a certain temperature may be similar.

It is reminded that the thermal mass of the material of the test room was low. A considerably slower temperature rise is to be expected if parts of the construction material consists of, for instance, concrete.

In conclusion, the present study indicates that, as regards displacement ventilated rooms during the heating period, people are less sensitive to the air temperature stratification than stated in the standards. More research is however needed in this matter, involving different clothing habits of the occupants at different times of the year, and also considering the fact that the thermal environment in densely populated rooms practically never is steady, but varies with time according to the occupancy.

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