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Thermal Interaction of Closely Spaced Persons

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SUMMARY

This paper presents results from a pilot study on the thermal interaction of closely spaced persons in a large enclosure. The surface temperature at different densities of persons is evaluated using a high-resolution thermovision camera in a controlled thermal environment. The corresponding thermal sensation is evaluated using questionnaires for the various densities. The results indicate that it may be acceptable to consider persons standalone, in a thermal sense, disregarding thermal interaction at usual densities in the design of large enclosures.

IMPLICATIONS

In the design of large enclosures with closely spaced persons like lecture rooms and concert rooms each person is usually considered standalone in a thermal sense. Implicitly, this fact assumes that no thermal interaction prevail either in terms of heat transfer or thermal sensation. This applies for the estimation of heat load for thermal building simulation as well as for thermal comfort design. However, there is a lack of investigations that validate this important and widely applied assumption in case of realistic person densities.

KEYWORDS

Thermal comfort, occupant density, occupancy, heat load, thermal interaction

INTRODUCTION

In building design occupants are usually treated standalone in the design process even though more occupants are present at the same time. In that way it is implicitly assumed that no thermal interaction between the occupants occurs to simplify the calculations and the design process. This applies for thermal comfort design (thermal sensation) where mutual interaction caused by e.g. thermal radiation is ignored as well as for thermal building simulation where the possible influence on occupants' surface temperature (heat load) is disregarded. In case of spacious enclosures the assumption seems obvious and sound; however, in case of closely spaced persons it may be less straightforward.

Only little work has been done on the topic over time since some of the early studies by Yaglou and Drinker (1928) and Rohles Jr. et al. (1967). For instance, Kang et al. (2001) investigated the surface, oral and armpit temperatures for various conditions. The present work is a pilot study on the thermal interaction of closely spaced persons. The validity of the prevailing hypothesis of thermal independence is examined for a realistic occupant density.

METHODS

Measurements are performed in a ventilated lecture room using various occupant densities, see Figures 1 and 2. Time-varying room surface temperatures, air temperatures and CO₂ concentrations are measured together with the surface temperature of the occupants. Calibrated thermocouples and a high-resolution thermovision camera enable a resolution of

approximately ± 0.1 °C, see Table 1. Apart from physical measurements subjective evaluations are performed using questionnaires on thermal sensation, perceived air quality, etc. The subjects are students pre-conditioned for some hours in nearby rooms before the measurements in the lecture room. The room air change rate is 1.7 h^{-1} corresponding to an airflow per person ranging from 9.4 – 156.7 l/s-person depending on the occupant density.

Two cases are examined. Case I with 60 subjects where occupant surface temperature is investigated as a function of time and location. Case II investigates the surface temperature and thermal sensation for four different occupant densities (four phases), see Table 2.

Table 1. Measuring points in lecture room. The co-ordinate system is defined in Figure 1.

No.	Location; Co-ordinates (x, y, z; in mm)
1 – 3	Surface temperature, wall 1; (4335, 0, 1000), (2765, 0, 3000), (2765, 0, 5000)
4 - 6	Surface temperature, wall 2; (0, 5280, 1000), (0, 5280, 3000), (0, 5280, 5000)
7 - 8	Surface temperature, wall 3; (7590, 10560, 2823), (7590, 10560, 4941)
9 - 10	Surface temperature, wall 4; (15900, 9030, 2823), (15900, 9030, 4941)
11 - 12	Surface temperature, ceiling; (7590, 2640, 6000), (7590, 7920, 6000)
13 - 15	Surface temperature, floor; (7590, 5493, 790), (7590, 7312, 1180), (7590, 9146, 1570)
16	Surface temperature, table row 4; (5123, 5261, 1550)
17	Surface temperature, table row 6; (5123, 7061, 1940)
18	Surface temperature, table row 8; (5123, 8861, 2330)
19	Air temperature and CO ₂ concentration, 100 mm above floor, rack 1; (2711, 7259, 1280)
20	Air temperature, 600 mm above floor, rack 1; (2711, 7259, 1780)
21	Air temperature and CO ₂ concentration, 1100 mm above floor, rack 1; (2711, 7259, 2280)
22	Air temperature and CO ₂ concentration, 2000 mm above floor, rack 1; (2711, 7259, 3180)
23	Air temperature and CO ₂ concentration, 100 mm above floor, rack 2; (5962, 6339, 1085)
24	Air temperature, 600 mm above floor, rack 2; (5962, 6339, 1585)
25	Air temperature and CO ₂ concentration, 1100 mm above floor, rack 2; (5962, 6339, 2085)
26	Air temperature and CO ₂ concentration, 2000 mm above floor, rack 2; (5962, 6339, 2985)
27	Air temperature and CO ₂ concentration, 100 mm above floor, rack 3; (8238, 7259, 1280)
28	Air temperature, 600 mm above floor, rack 3; (8238, 7259, 1780)
29	Air temperature and CO ₂ concentration, 1100 mm above floor, rack 3; (8238, 7259, 2280)
30	Air temperature and CO ₂ concentration, 2000 mm above floor, rack 3; (8238, 7259, 3180)
31	Air temperature and CO ₂ concentration, 100 mm above floor, rack 4; (10504, 8160, 1475)
32	Air temperature, 600 mm above floor, rack 4; (10504, 8160, 1975)
33	Air temperature and CO ₂ concentration, 1100 mm above floor, rack 4; (10504, 8160, 2475)
34	Air temperature and CO ₂ concentration, 2000 mm above floor, rack 4; (10504, 8160, 3375)
35	Air temperature and CO ₂ concentration, 100 mm above floor, rack 5; (13475, 7259, 1280)
36	Air temperature, 600 mm above floor, rack 5; (13475, 7259, 1780)
37	Air temperature and CO ₂ concentration, 1100 mm above floor, rack 5; (13475, 7259, 2280)
38	Air temperature and CO ₂ concentration, 2000 mm above floor, rack 5; (13475, 7259, 3180)
39	Supply air temperature and CO ₂ concentration; (300, 6508, 4750)
40	Exhaust air temperature and CO ₂ concentration; (15860, 2260, 0)
41 - 43	Surface temperature below table; (7590,5493,1550), (7590,7312,1940), (7590,9146, 2330)
44	Surface temperature of persons; (15852, 1500, 2930)

Table 2. Case II subject information (mean values)

Phase	No. of persons (male/female)	Age (years)	Weight (kg)	Surface area (m ²)	Clothing insulation (clo)
1	41/9	23	77	1.96	0.66
2	20/4	23	79	2.00	0.68
3	10/0	24	83	2.04	0.80
4	3/0	26	86	2.10	0.74

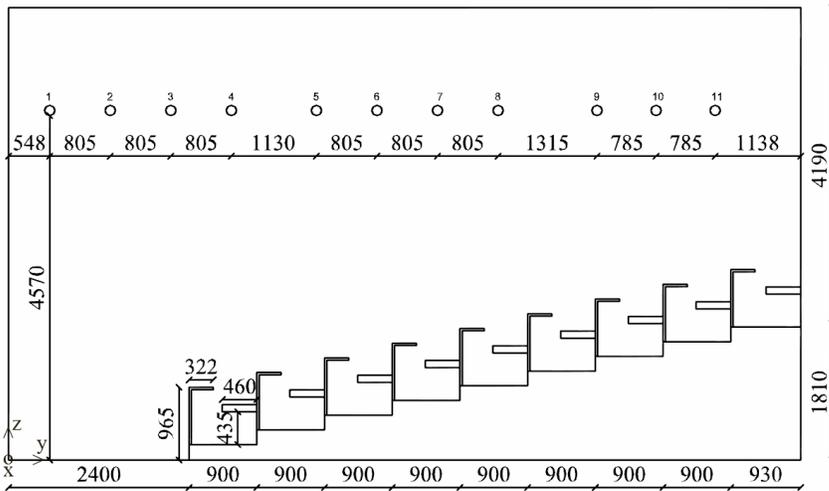
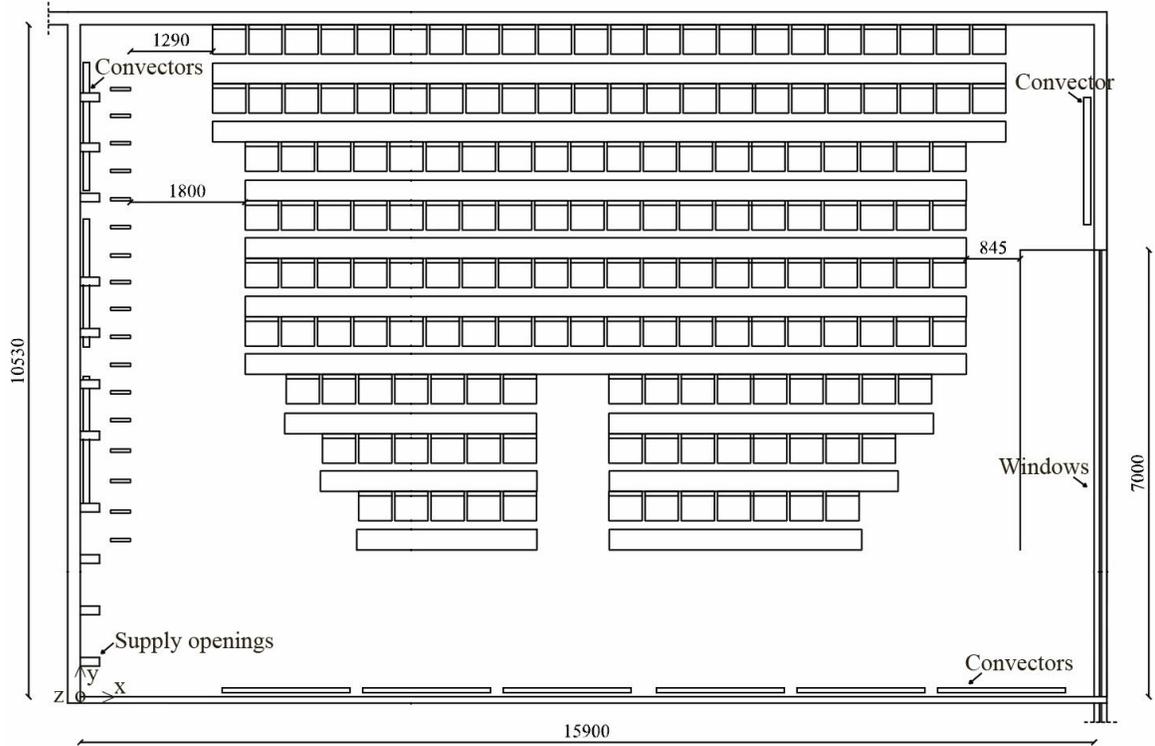
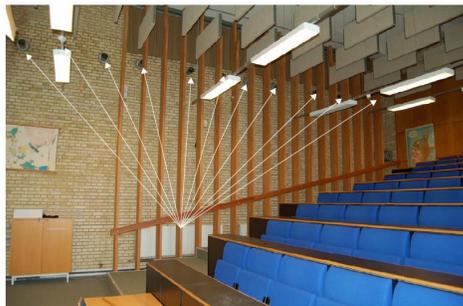


Figure 1. Dimensions of the lecture room applied for the measurements (in mm).



(c) Supply air devices

(d) Close-up

Figure 2. Supply openings for lecture room ventilation. Exhaust openings are located in the floor opposite the supply openings.

RESULTS

In Case I the surface temperature of 60 subjects at a typical density setting is investigated over approximately 45 minutes (typical lecture duration). No significant occupant surface temperature gradient is found neither in time nor location.

Case II comprises four phases corresponding to four consecutive occupant densities, see Figure 3. Each phase has duration of approximately 17 minutes. After 13 minutes the subjects are asked to complete a questionnaire. The surface temperature of eight selected persons (small circular areas below numbers) is investigated in more detail, see Table 3.

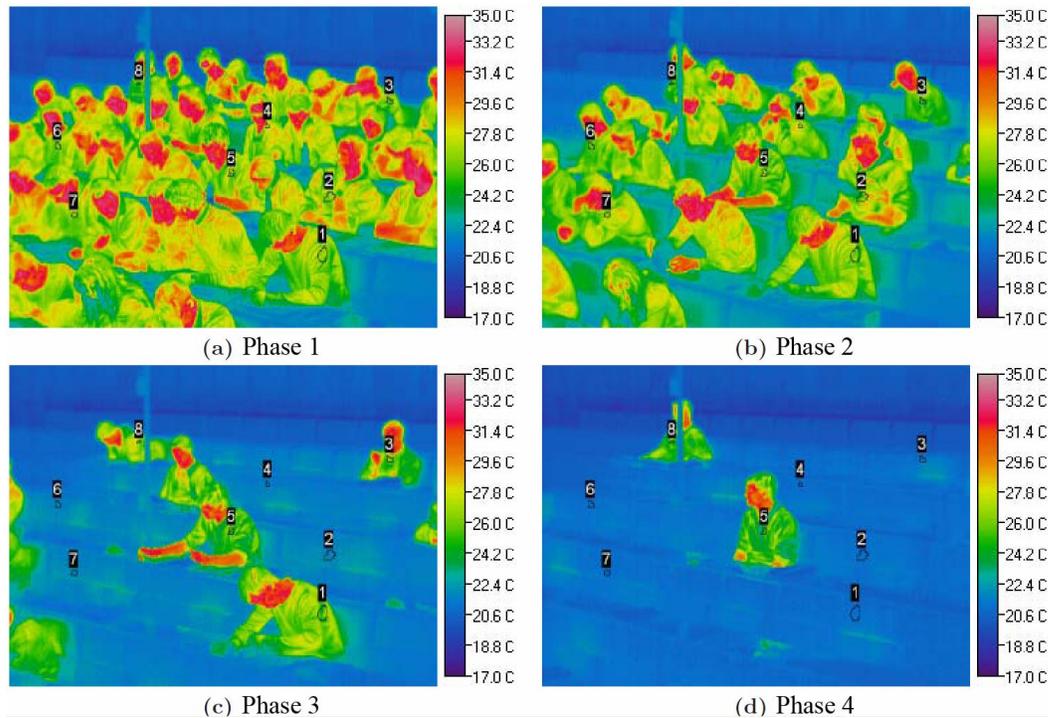


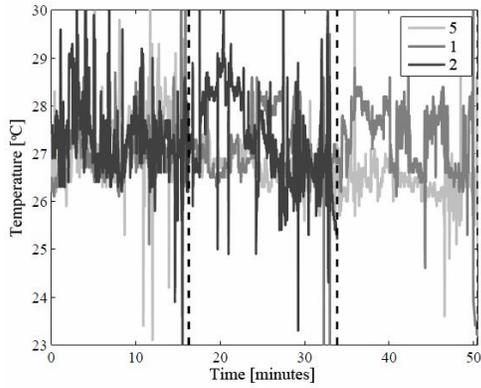
Figure 3. Surface temperature of subjects in Case II (after 10 minutes duration of each phase).

Table 3. Surface temperature of 8 selected persons from Case II. Temperature is measured each second by thermovision and determined as the average temperature of the circular areas shown below each number in Figure 3 (diameter approximately 5 cm).

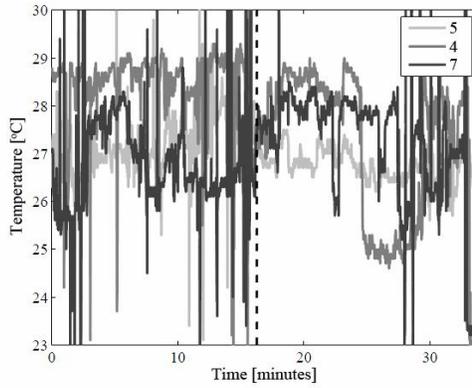
Phase	Person [°C] (time-weighted mean value)							
	1	2	3	4	5	6	7	8
1	27.0	27.7	26.4	28.3	26.9	26.9	26.1	26.7
2	27.1	27.3	26.5	27.7	27.0	26.8	27.1	26.5
3	27.2	-	26.1	-	26.4	-	-	26.6
4	-	-	-	-	26.0	-	-	26.2

Figure 4a-d shows the time-varying surface temperature corresponding to Figure 3 and Table 3. Figure 4e-h shows the thermal sensation of all subjects for the four phases (densities).

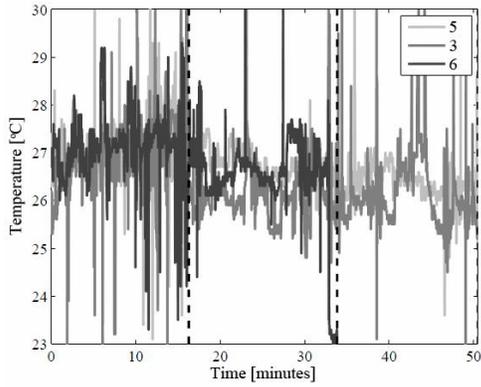
Apart from the findings reported acceptability is determined for temperature (84%, 75%, 70%, and 67% for phases 1 – 4, respectively), indoor air quality (88%, 92%, 90%, and 100% for phases 1 – 4, respectively) and air movements (84%, 58%, 90%, and 67% for phases 1 – 4, respectively).



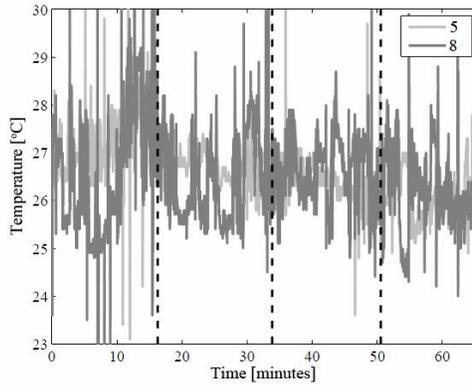
(a) Person 1, 2 and 5; Phases 1 - 3



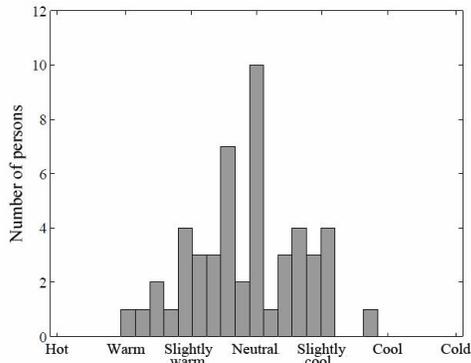
(b) Person 4, 5 and 7; Phases 1 - 2



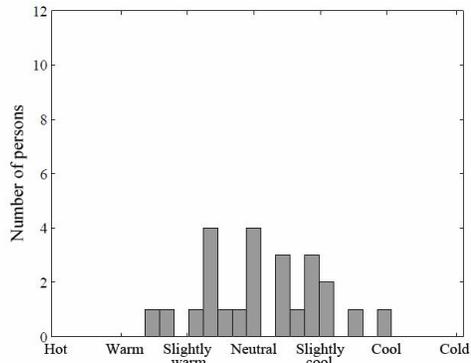
(c) Person 3, 5 and 6; Phases 1 - 3



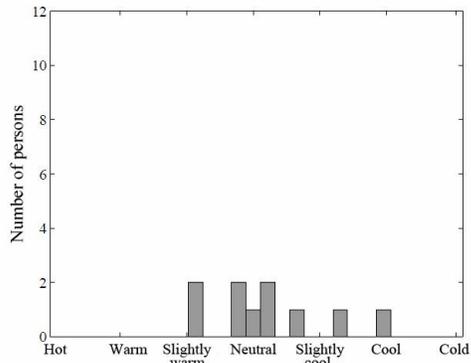
(d) Person 5 and 8; Phases 1 - 4



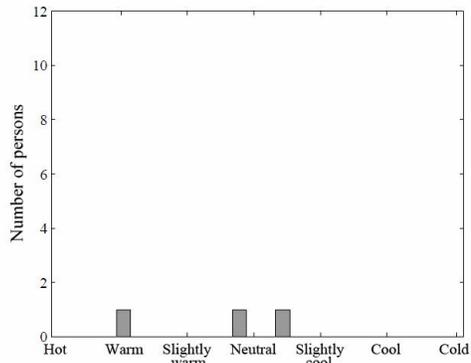
(e) Phase 1; 50 persons



(f) Phase 2; 24 persons



(g) Phase 3; 10 persons



(h) Phase 4; 3 persons

Figure 4. a – d: Time-varying occupant surface temperature (person number found in Figure 3). e – h: Thermal sensation rated on standard 7-point scale reported from questionnaires.

DISCUSSION

Table 3 indicates how the surface temperature of eight selected persons varies for each of the four phases corresponding to decreasing occupant densities. Some persons are chosen to be in the centre area (e.g. person 5) whereas others are located peripherally (e.g. person 8). After each phase a number of persons are leaving the room to reduce the density, thus, only two out of eight are present in all phases. Figure 4a-d shows the surface temperatures as a function of time. The substantial and fast variations are caused by the person's movements or by the occasional interference by a body part of a neighbouring person. The corresponding thermal sensation is reported in Figure 4e-h indicating an approximately neutral thermal sensation on average for each phase.

If the surface temperature in this case is influenced by thermal interaction it may be expected that the temperature is changed, probably reduced, when the occupant density is reduced. At the same time some influence of relative location in the occupant crowd may be expected, where the surface temperature in case of peripheral location would deviate from centre location. The results, however, do not show consistent behaviour as related to the above hypothesis.

In general the pilot study, Case I as well as Case II, does not indicate a significant influence of occupant density in shape of thermal interaction for a realistic setting. If the density was increased beyond typical settings in lecture rooms, cinemas, larger meeting rooms, etc. an influence might be found, however, this work considers realistic settings only. The relatively few subjects and cases in the pilot study should obviously be expanded in future work to generate more accurate information.

The findings support the generally accepted, but not much verified, assumption of mutual thermal independence of multiple persons in usual settings. Thus, it seems that it is acceptable to consider persons standalone, in a thermal sense, in case of thermal comfort design and generation of boundary conditions for thermal building simulation and computational fluid dynamics.

CONCLUSIONS

This paper presents results from a pilot study on the thermal interaction of closely spaced persons in a large enclosure. The surface temperature at different densities of persons is evaluated using a high-resolution thermovision camera in a controlled thermal environment. The corresponding thermal sensation is evaluated using questionnaires for the various densities. The results indicate that it may be acceptable to consider persons standalone, in a thermal sense, disregarding thermal interaction at usual densities in the design of large enclosures.

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