Impact of personal factors and furniture arrangement on the thermal plume above a human body

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SUMMARY

Thermal flows generated by office equipment and lighting will be less important in future buildings due to development of low power consumption devices. Consequently, occupants will become one of the major sources of thermal flows in rooms. The influence of type of clothing and chair design on the characteristics of the thermal plume above a person was studied. Experiments were performed in a climate chamber with mean radiant temperature equal to the room air temperature, no radiant temperature asymmetry, and air velocity lower than 0.05 m/s. A female thermal manikin simulated a sitting occupant. The results reveal that the convective heat loss from the body changes inverse proportionally to the clothing thermal insulation and affects the enthalpy excess in the plume. Chair design changes the ratio between convection and radiation heat losses from the body and has significant impact on the thermal plume above a sitting person. The results can be applied in CFD simulations and full-scale mock-up validation of room air distribution.

INTRODUCTION

Air distribution in rooms is a result of a complex interaction between flows generated by heat sources (humans, computers, light, etc.), convection flows generated by cold or warm surfaces, and forced flows generated by the ventilation system. Thermal flows generated by office equipment (computers, monitors, etc.) and lighting will be less important in the future due to the development of low power consumption devices (LCD screens, halogen lamps, etc.). In the future, occupants will therefore generate the major thermal flows in rooms. The volume flux of the thermal plume is comparable to the ventilation flow volume, so it has impact on the air distribution in a room. Convective streams should be understood and included in indoor environment design to ensure a proper interaction with mechanical ventilation. However, only limited information on the thermal plume generated by a human body is available.

The difference between the room air temperature and the body surface temperature as well as the body size are the most important factors, which determine the characteristics of the thermal plume above a human body. However, personal factors including body posture, clothing design, level of baldness as well as furniture design and arrangement may also affect the plume.

The phenomenon of the airflow generated by a human body represents an interesting case of a convective flow arising from an extensive heat source. Maintaining life entails exothermic chemical processes, which is commonly known as metabolism. The rate of metabolism is greatly influenced by the amount of work being done by the body and varies over time and between individuals. High levels of work or activity generate high levels of excess heat that must be dissipated by the body in order to maintain a constant temperature. One can use the basic heat balance equation for a human body [1] to calculate the amount of convective heat emission by a human body to the environment. Trzeciakiewicz et al. [2] proposes an equation from which the enthalpy excess in the plume in an easy way can be determined, based on the convective part of the heat emitted by a heat source and the stratification in the plume surroundings.

Honma [3] describes the fundamental phenomenon of the airflow generated by a human body. The metabolic heat emission from the human body causes an airflow around it with velocities, which can exceed 0.2 m/s and even reach 0.5 m/s locally. Natural convection becomes stronger when the temperature difference between the surface of clothing and the ambient air increases. It was suggested [3] that the free convection generated by occupants can have a strong impact on the airflow in the room and can influence the efficiency of a ventilation system. An investigation by Mierzwinski [4] of the thermal plume above a real person, sitting or standing, provided scatter of mean velocity resulting from human behaviour and air stratification. It was observed that the wandering of the plume axis was related to the instability of the flow in the plume. Temperature and velocity profiles in the plume started to become quasi-Gaussian in shape at the height of 0.5 m above the human head, i.e. self-similarity zone in the mean flow occurred. The conclusion was that in dwellings and office rooms under normal conditions and air temperature between 19 and 23ºC, a convective plume can be treated as formed at the level of 0.75 m above the head of a sitting or standing person. At this height, the volume flux of the thermal flow is in the range 0.03 - 0.06 m^3/s and causes an air movement comparable to inlet streams. Hyldgaard [5] investigated the air velocity distribution above the head of a breathing and non-breathing, sitting or standing, dressed thermal manikin. The measurements showed that breathing had hardly any effect on the velocity above the head because exhaled air from the nose acts solely as a warm “cloud” outside the measuring zone. The temperatures measured in the plume with too low temperature excess were not analysed due to insufficient accuracy. The flow above the head of a sitting person was described as an axis-symmetrical Gaussian plume, although velocities were found to be higher above the legs than behind the back.

The impact of thermal insulation caused by clothing and chair on the development of the thermal plume generated by a sitting person has not been studied yet. As reported by McCullough et al. [6] the insulation of the clothing is different when a person is in a seated position (net chair) in comparison to a standing position. The clothing insulation is lower for a seated posture because the insulation provided by the air layer around the body is reduced due to the posture as well as due to a smaller amount of air trapped in the clothing layer. A chair adds to the clothing insulation differently depending on its design, e.g. surface area in contact with the body, the material and the thickness as well as the clothing ensembles worn.

The objective of the present study is to identify the impact of clothing insulation and chair design on the characteristics of the thermal plume above a seated human body.

FACILITIES AND EQUIPMENT

Climatic chamber

The experiments were performed in a climatic chamber at the International Centre for Indoor Environment and Energy at the Technical University of Denmark. The chamber (4.7×5.8×2.5 m) is ventilated by an upward piston flow through a floor built of a porous sheet covered by a steel floor grating. The air is exhausted through a perforated ceiling. The construction of the chamber [7] ensures a condition with uniform temperature field and air velocity lower than 0.05 m/s. The double walls of the chamber consist of vinyl sheets forming a curtain distanced 1.6 cm from the solid mother wall. Approx. 85% of the controlled air coming from the space beneath the floor is supplied to the chamber through the floor, whereas the remaining 15% is vented through the space behind the wall curtains. This ensures a mean radiant temperature equal to the room air temperature and negligible radiant temperature asymmetry.

Thermal manikin

A thermal manikin with body size of an average Scandinavian woman (size 38, height 1.68 m) was used to simulate the dry heat loss of a sitting occupant. The manikin body is divided into 17 individually controlled segments and is monitored by a personal computer. Adjustment of the manikin to a realistic sitting posture is possible due to movable junctions in neck, shoulder, hip and knees. The entire surface area of the manikin is covered with closely-wound nickel wires in thermal contact with the body shell. Measurement of the resistance of the wiring for each section yields the mean surface temperature of each body part. During the investigation, the manikin was controlled to have a surface temperature of its segments equal to the skin surface temperature of an average person in the state of thermal comfort, i.e. “comfort mode” control [8].

Set up

During the experiments, the thermal manikin was placed in the centre of the climatic chamber. A wooden plate was placed beneath the manikin, covering the floor 1.25 m to the front of the manikin and 0.75 m to the other three sides measured from the centre of the manikin head. The exhaust area in the ceiling was reduced to 1.8×1.8 m in the centre of the room above the manikin.

Simultaneous measurements of air velocity and temperature in the plume were performed by 16 omnidirectional velocity sensors and 17 constantan-copper thermocouples fixed on a long horizontal arm of a traversing system. The velocity probes were placed 0.1 m apart of each other. The thermocouples were placed between the velocity probes as well as 0.05 m before the first probe and 0.05 m after the last probe. The arm was placed parallel to the symmetry axis of the manikin (Figure 1).

Another construction with 29 constantan-copper thermocouples fixed on two diagonals of a horizontal squared frame was used to measure temperatures in the plume. The thermocouples were positioned in a distance from the centre of: 0, 4, 8, 14, 22, 32, 44 and 90 cm.

Furthermore, the vertical temperature gradient in the chamber was registered with 13 thermocouples fixed on a stand positioned at a distance of approx. 0.8 m from the manikin feet. The thermocouples were connected to two multichannel thermometers registering the temperatures with a resolution of 0.01 K.

Figure 1. Position of sensors at the level of 0.7 m above the manikin head.

METHODS

During the measurements the condition in the chamber was: air temperature 23°C, vertical temperature gradient approx. 0.07 K/m, and air velocity less than 0.05 m/s.

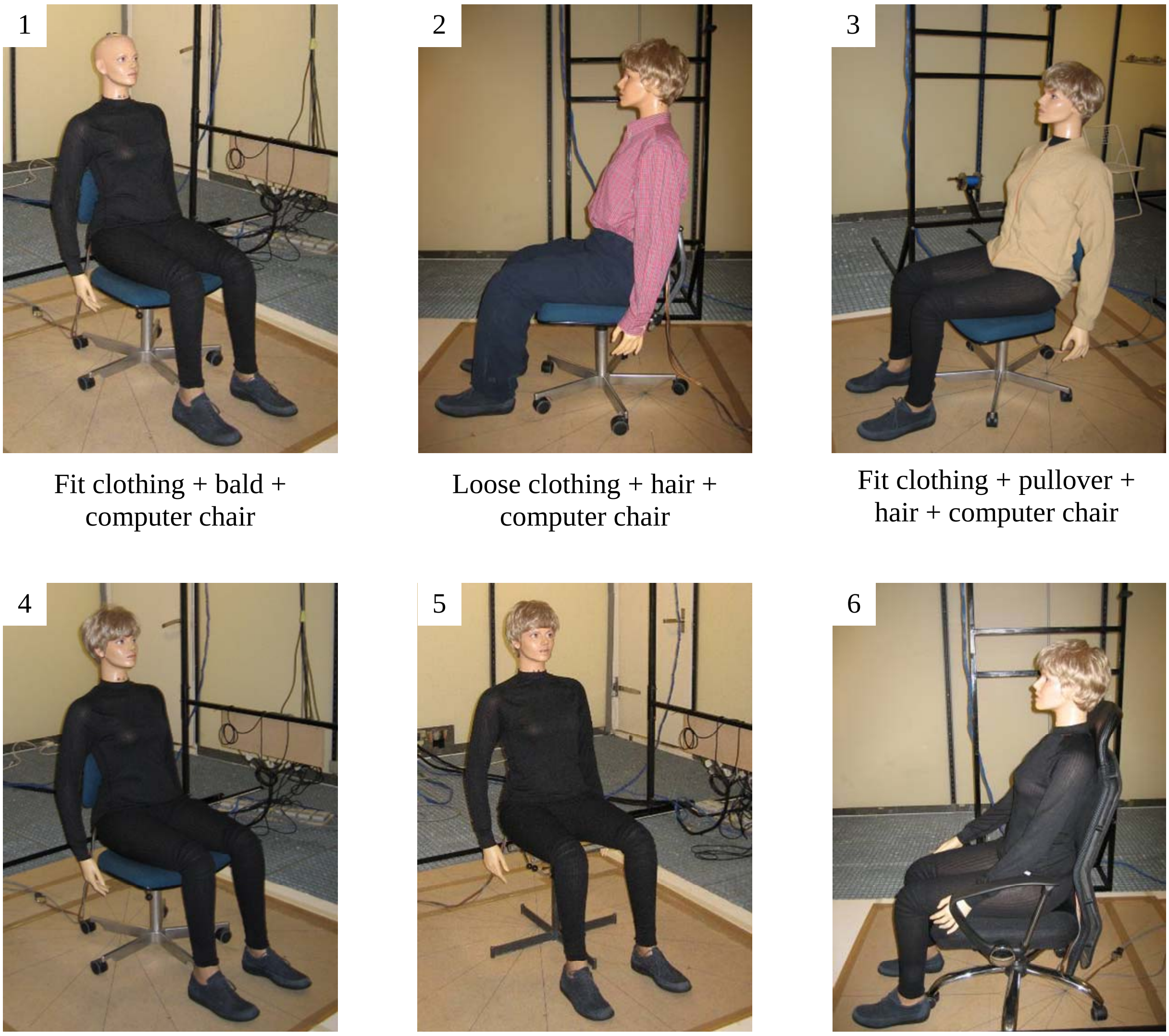
Thermal plumes were measured for six different cases comprising the thermal manikin dressed in different clothing and sitting on three different chairs, as shown in Figure 2.

Simultaneous measurements of air velocity and temperature in the plume were performed at the height of 0.7 m above the head of the seated thermal manikin. The arm with the sensors was moved in steps of 0.1 m from the left side of the manikin to the right side. In this way, rather dense measurement grid was achieved covering an area of 1.9 m^2 above the head of the manikin.

The averaging and interval time for one measurement was 5 minutes and the total recording time in one position of the arm with the sensors was 15 minutes, thus consisting of three measurements. The data obtained from the last 5-minute interval were used for the calculations, leaving the first 10 minutes for the condition to become stable after changing the position of the arm.

The thermocouples, mounted on the frame positioned at a level of 0.71 m above the manikin, registered simultaneously the temperature in the plume in order to be able to define possible plume axis wandering.

A separate study by Zukowska et al. [9], however, showed that plume axis wandering was not significant in the case of a sitting manikin, and this was therefore not taken into account in the calculations. An assumption about Gaussian distribution of the air temperature and velocity would be incorrect due to the impact of the body geometry on the development of the plume and a significant asymmetry in the profiles of the parameters in front of the manikin [9].



1: Fit clothing + bald + computer chair

2: Loose clothing + hair + computer chair

3: Fit clothing + pullover + hair + computer chair

4: Fit clothing + hair + computer chair

5: Fit clothing + hair + light support

6: Fit clothing + hair + executive chair

Figure 2. Studied cases of thermal plumes above a thermal manikin dressed with different clothing and sitting on various types of chairs.

Based on registered temperature excess Δt_i and air velocity w_i in each measuring point, for area Δs of 0.1×0.1 m, integral parameters were identified according to the equations [10]:

- enthalpy flux: $Q = \rho \cdot c_p \sum (\Delta t_i \cdot w_i) \cdot \Delta s$, (1)
- volume flux: $V = \sum w_i \cdot \Delta s$, (2)
- buoyancy flux: $P = \rho \cdot g \cdot \beta \cdot \sum \Delta t_i \cdot \Delta s$, (3)
- momentum flux: $I = \rho \cdot \sum w_i^2 \cdot \Delta s$, (4)

where ρ is air density (kg/m^3), c_p is specific heat of air (J/kgK), g is acceleration of gravity (m/s^2), and β is thermal expansion coefficient (1/K).

In order to compare the impact of the different clothing and chair design on the shape of the thermal plume, it was chosen to use thermal insulation as the basic parameter describing each of the cases. The thermal insulation was calculated according to ISO 15831:2004 [11] based on the results obtained with the thermal manikin, i.e. the heating power supplied to each body segment and the segmental skin surface temperature, in each of the tested cases.

The convective part of heat losses Q_c for each case was defined based on the equation [2]:

$$Q_c = Q + \frac{3}{8} \cdot Q^{1/3} \cdot \rho \cdot c_p \cdot k_v \cdot S \cdot z^{8/3}, \qquad (5)$$

where Q is enthalpy flux (W), ρ is air density (kg/m^3), c_p is specific heat of air (J/kgK), k_v is entrainment coefficient, S is thermal stratification (K/m), and z is the distance from the measuring plane to the plume origin (m).

Based on research by Popiolek et al. [12] an entrainment coefficient k_v equal to 0.006 was used in the calculations. The distance from the top of the heat source to the origin z was assumed to be 1.7 m. The thermal stratification S in the chamber during the investigation was measured to be 0.07 K/m as mentioned previously.

The integral parameters were presented as values proportional to the convective part of the emitted heat with adequate power, as given by Popiolek [13] based on the similarity hypothesis:

$$w \sim Q_c^{1/3}, \qquad \Delta t \sim Q_c^{2/3}, \qquad (6, 7)$$

Consequently, the volume flux V is given as a relative value to the convective heat loss Q_c in power 1/3, and the momentum flux I and the buoyancy flux P are presented as relative values to the convective heat loss Q_c in power 2/3.

RESULTS AND DISCUSSION

In order to compare the results for the six investigated cases, the thermal insulation of the clothing and chair was calculated based on the manikin measurements. Figure 3 shows the correlation of power supplied to the manikin as a function of the thermal insulation I_{cl+ch}. As it can be seen there is a clear trend that less power is supplied at higher *clo* values, as expected when the manikin control was set to comfort mode. The thermal insulation values, which were reduced by the insulation of the air layer around the nude manikin sitting on a light support, are listed in Table 1.

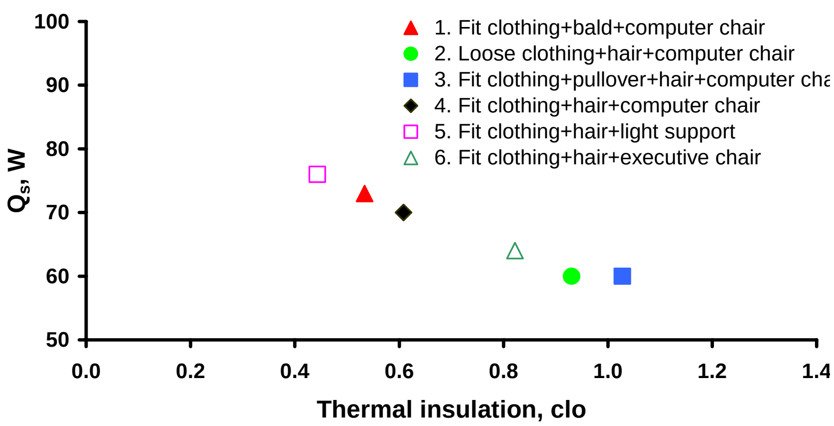


Figure 3. Power supplied to the manikin as function of clothing and chair insulation.

Figure 4 shows that the changes of clothing do not affect the proportion between the convective heat and power supplied to the manikin, and it can be said that this relation is constant. The ratio decreases from 30% to 24% when the chair is changed from a computer chair to a light support, and increases up to 40% when the light support is replaced by the executive chair. It is not the thermal insulation, which is the main factor determining the convective heat losses from a heat source, but the chair design. The light support almost does not protect the body from the surroundings. This is why the convective part of the heat losses decreases due to the larger radiation heat exchange. In the case with the manikin sitting on the executive chair, the amount of body surface area in contact with the chair is much bigger, and therefore the chair protects from heat loss through radiation and at the same time convective heat exchange increases.

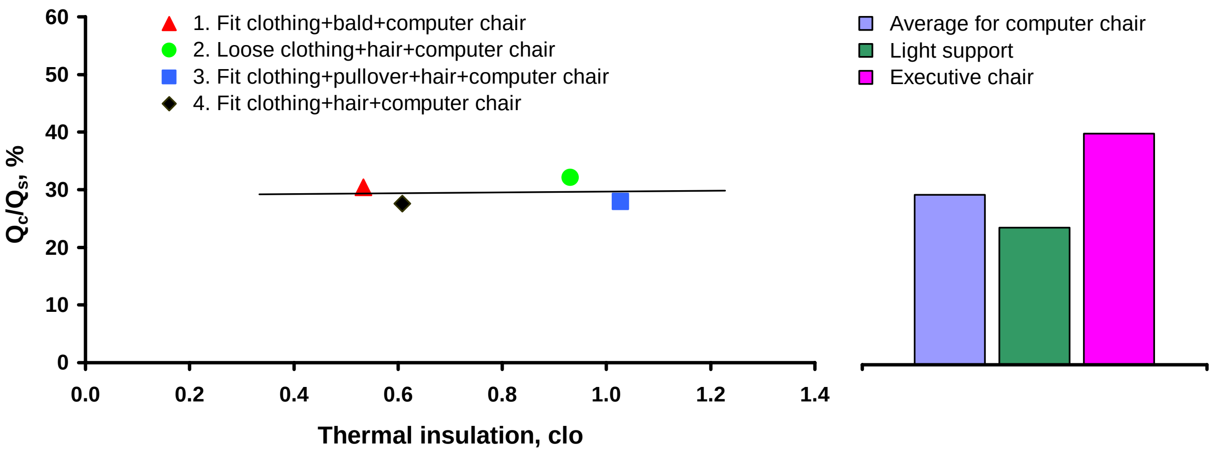


Figure 4. Ratio of convective heat to power supplied to the sitting manikin as function of clothing and chair insulation.

The results show that the assumed proportion of the integral parameters to the convective heat loss in an appropriate power is not completely fulfilled when the ratio of convection to radiation heat losses changes. As presented in Table 1, the values for the executive chair are slightly different from those obtained for cases with the computer chair.

Table 1. Integral parameters of thermal plumes related to convective heat losses from the sitting manikin.

No	Factors	I_{cl+ch}	Q_c	$V/(Q_c)^{1/3}$	$I/(Q_c)^{2/3}$	$P/(Q_c)^{2/3}$
		clo	W	$m^3/(sW^{1/3})$	$N/W^{2/3}$	$kg/(s^2W^{2/3})$
1	Fit clothing + bald +computer chair	0.534	22.2	0.029	0.0014	0.00063
2	Loose clothing + hair + computer chair	0.930	19.3	0.030	0.0015	0.00072
3	Fit clothing + pullover + hair + computer chair	1.027	16.8	0.028	0.0015	0.00063
4	Fit clothing + hair + computer chair	0.608	19.3	0.029	0.0015	0.00063
5	Fit clothing + hair + light support	0.443	18.1	0.030	0.0015	0.00057
6	Fit clothing + hair + executive chair	0.822	25.7	0.026	0.0013	0.00072

CONCLUSIONS

- The convective heat loss from the body changes inverse proportionally to the clothing thermal insulation (clo value) and in the same way, it changes the enthalpy excess in the plume. Consequently, according to the similarity hypothesis of plumes, volume, momentum and buoyancy fluxes of the thermal plume above a sitting manikin changes.
- Chair design has significant impact on the thermal plume development above a seated person and has to be considered when furnishing offices. Chair design changes the ratio between convection and radiation heat losses from the body.
- More detailed studies on the impact of the radiation and convection heat exchange between the human body and the surrounding environment on the development of thermal plumes are recommended.

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