Thermal plume above a simulated sitting person with different complexity of body geometry

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SUMMARY

Occupants are one of the main heat sources in rooms. They generate thermal plumes with characteristics, which depend on geometry, surface temperature and area of the human body in contact with the surrounding air as well as temperature, velocity and turbulence intensity distribution in the room. The characteristics of the thermal plume generated by a sitting person were studied using four human body simulators with different complexity of geometry but equal surface area: a vertical cylinder, a rectangular box, a dummy, and a thermal manikin. The results show that the dummy and the thermal manikin generate almost identical thermal plumes. Therefore, with respect to the generated thermal plume, the dummy can be successfully used as a simulator of a sitting person. The cylinder and the rectangular box generate much more concentrated plumes than the thermal manikin but can correctly simulate enthalpy flux and buoyancy flux.

INTRODUCTION

Occupants are major heat and pollution sources in buildings. Thermal flows generated by a human body have a significant impact on the room air distribution. The phenomenon of the thermal plume above a heat source has been reported in the literature [1,2] as being influenced by a large number of factors such as air temperature, velocity and turbulence intensity distribution in the surrounding air, as well as the dimensions of the room. The initial flow caused by a heat source depends on the area, geometry and surface temperature of the source.

The investigation of thermal plumes necessitates sophisticated measuring techniques because air velocity and temperature excess are small and difficult to measure. Moreover, the phenomenon of plume axis wandering, i.e. deviation of maximum values of temperature excess and velocity from the vertical symmetry axis of the heat source, has to be considered. It was concluded by Popiolek [3] that plume axis wandering is caused by flow instability due to changes in the environmental conditions. In order to avoid the influence of the wandering phenomenon on the scatter of the measurement results, a measuring and data processing method was developed [1]. Kofoed and Nielsen [4] called this an extrapolation method.

An investigation of the thermal plume with a real person as a heat source causes numerous problems due to the person's behaviour [5]. Using a human simulator instead eliminates difficulties connected with an unstable heat source. Among the simplest simulators of a person, sitting or standing, a heated cylinder is commonly used in full-scale measurements. Kofoed and Nielsen [4] investigated the thermal plume above a vertical cylinder (diameter 0.4 m and height 1 m) simulating a sitting person to validate the extrapolation method. Bjørn and Nielsen [6], when dealing with merging thermal plumes from heat sources situated in the vicinity of each other, used two steel cylinders of diameter 0.4 m and height 1.0 m as simple models of human beings. Borges et al. [7] compared a heated cylindrical dummy with four circular openings close to the top (as suggested in DIN 4715-1 [8]) and a thermal manikin with results obtained with a real person. They concluded that such a dummy cannot be used to simulate a sitting person due to the openings, which caused the plume to have two maxima far away from the axis of the cylinder. The results showed that buoyancy driven flow above the manikin is quite similar to that obtained with a sitting person. A rectangular geometry is most often used in CFD models to predict the local airflow around a person and personal exposure. The most simple can be a heated cuboid, and the most complex includes legs and head [9]. The most advanced human body simulator, a thermal manikin, is controlled to keep the body surface temperature similar to the skin temperature of an average person in the state of thermal comfort. Using such simulators gives a possibility to identify the impact of personal factors (clothing insulation, etc.) on the development of the thermal plume emitted by a human body [10] or impact of breathing [11].

The possibilities of simulating a human body are numerous. It is important to determine how far it is possible to simplify the geometry of the human body in full-scale experiments and CFD simulations, and still get valid results. The objective of this study is to identify the degree to which an accurate simulation of the body shape is of importance for the characteristics of the generated thermal plume.

FACILITIES AND EQUIPMENT

Human body simulators

The characteristics of the thermal plume generated by a sitting person were experimentally measured using four human body simulators with different complexity of geometry, including a vertical cylinder, a rectangular box, a dummy, and a thermal manikin (Figure 1). The surface area of the simulators was approximately the same and in the range of 1.60-1.63 m^2.

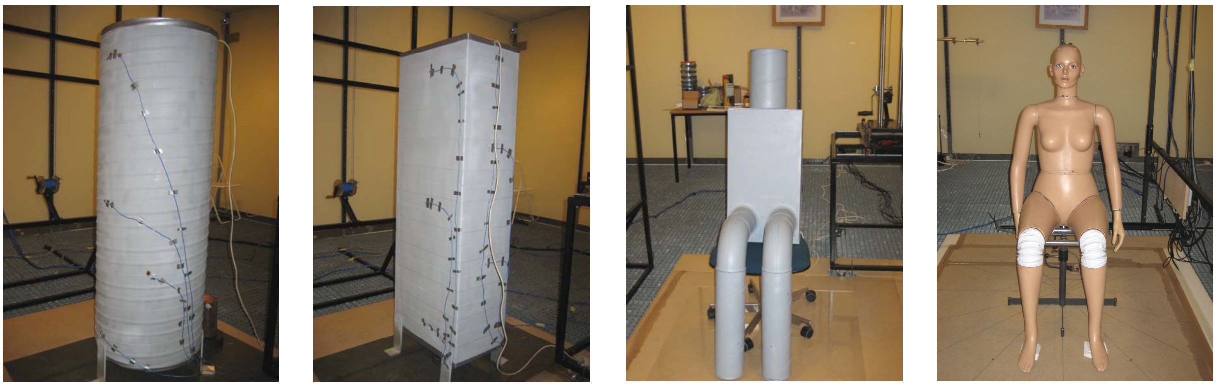

Figure 1. Human body simulators – cylinder, rectangular box, dummy and thermal manikin.

The simplest simulator of a sitting human body was made of a cylindrical steel duct with a diameter of 0.40 m and a height of 1.10 m (surface area of 1.63 m^2). Another simulator was made of a rectangular duct with dimensions of 0.40×0.25 m and a height of 1.10 m (surface area of 1.63 m^2). Both the cylinder and the box were placed on 10 cm high legs in order to ensure a height of the simulators equal to the height of a sitting thermal manikin. The top and the bottom of the simulators were closed with tight covers and they were painted in grey in order to achieve correct radiation. A stand with four 25 W electrical bulbs and three small fans were fixed inside the simulators while supplied power was adjusted by a transformer.

The third sitting person simulator, the dummy, is built of cylindrical and rectangular steel ducts painted in grey. It has a head, a trunk and legs, but no arms. Its surface area is 1.60 m^2. Six electrical bulbs of different power are placed inside the dummy. The power to the bulbs and the fans mixing the air inside the simulator is adjustable.

A 17-segmental female thermal manikin (size 38, height 1.68 m) was the most advanced simulator with movable junctions in neck, shoulder, hip and knees to adjust its posture to a real sitting or standing person. The entire surface area of the manikin is covered with nickel wire 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. All body segments are individually controlled to keep their surface temperature equal to that of an average person in the state of thermal comfort (known as “comfort” mode of control) [12].

Climatic chamber

The measurements were conducted in a climatic chamber (4.7×5.8×2.5 m) at the International Centre for Indoor Environment and Energy, Technical University of Denmark. The upward piston flow used for ventilating the chamber creates conditions with low vertical temperature gradient and air velocity less than 0.05 m/s. The special construction of the chamber [13] ensures conditions with mean radiant temperature equal to the room air temperature and negligible radiant temperature asymmetry.

Set up

During the experiments, the simulator was placed in the middle of the climatic chamber on a wooden plate of dimensions 1.5×2.0 m in order to avoid disturbances from the upward ventilation flow. The exhaust panels in the ceiling were closed, except for a 3×3 panel section (1.8×1.8 m) in the middle of the room above the source through which the air was removed.

In the case of the cylinder and the rectangular box, multipoint simultaneous measurements of air velocity and temperature in the plume were performed by an 8-channel omnidirectional thermoanemometer and a 30-channel thermometer (Figure 2). The spherical air velocity sensors were positioned in the plume on two perpendicular arms fixed on a specially designed traversing mechanism with two trolleys facilitating positioning of the velocity transducers within the horizontal measuring area. The position of the 8 anemometers relative to each other was constant and the distance between each two adjacent sensors was 24 cm.

The set up was modified while performing measurements above the dummy and the thermal manikin because the thermal plumes obtained in these two cases were wider and asymmetrical. The simultaneous measurements of air velocity and temperature in the plume were performed, using 16 omnidirectional velocity sensors and 17 constantan-copper thermocouples fixed on a horizontal arm of a traversing system parallel to the symmetry axis of the manikin.

Figure 2. Basic position of sensors and set up for testing the cylinder and the rectangular box (left and middle), and set up for testing the dummy and the thermal manikin (right).

In all of the experiments, another set of 29 thermocouples was fixed on two diagonals of a horizontal squared frame, positioned at a level of 0.71 m above the simulator. The thermocouples were positioned in a distance from the centre of: 0, 4, 8, 14, 22, 32, 44 and 90 cm. The thermocouples registered simultaneously the temperature in the plume in order to define possible plume axis wandering. Additionally, vertical profiles of the temperature in the chamber at a certain distance from the heat source were registered with thermocouples fixed on a stand. Thermocouples were connected to multichannel thermometers (resolution 0.01 K).

METHODS

Experimental conditions

The condition in the chamber was always: air temperature 23°C, low thermal stratification approx. 0.07 K/m, and air velocity less than 0.05 m/s. The air velocity and temperature measurements were performed at three heights of 0.5, 0.7 and 0.9 m above the simulator but this paper presents only results obtained at the height of 0.7 m.

The averaging and interval time for one measurement was in all cases 5 minutes and total recording time in one position of the anemometers was 15 minutes. Only data obtained after 10 and 15 minutes of recording were used for the calculations, leaving the first 5 minutes for the condition to stabilise between two measurements.

During the experiments, the dummy or the nude and bald manikin, in a posture realistic for a person, was seated on a light chair consisting of only a few bars supporting the body. The power supplied to the bulbs and fans inside the cylinder, rectangular box and dummy was adjusted to 100 W as supplied to the nude sitting thermal manikin.

Method of measuring and data analysis

The thermal plume above the cylinder and the rectangular box was identified by simultaneous multipoint measurements of air velocity and temperature in the plume, which facilitated the determination of the actual position of the plume axis. Measurements of air velocity were performed in a total of 13 positions at each height by moving the perpendicular arms with sensors in steps - basic position and 3 positions to the right, 3 to the left, 3 backwards and 3 forwards covering an area of approx. 1×1 m above the simulator. The number of measuring points was 104.

During the analyses of the data obtained for the cylinder and the rectangular box, it was assumed that temperature excess and air velocity profiles had Gaussian distribution, and they were described based on the following equations [3]:

$$\overline{w}_z = \overline{w}_{zm} \exp\left[(-r/R_w)^2\right], \quad \Delta\bar{t} = \Delta\bar{t}_m \exp\left[(-r/R_t)^2\right], \qquad (1, 2)$$

where $\overline{w}_z$ ($\overline{w}_{zm}$) is air velocity in the thermal plume (axis), $\Delta\bar{t}$ ($\Delta\bar{t}_m$) is temperature excess (axis), r is radius distance, R_t and R_w are temperature excess and velocity profile widths (the distance from the axis to the point where the parameter is e times lower than the axial one).

In order to avoid scatter of the measurements due to wandering of the plume axis, it was necessary to determine the actual plume axis position relative to the sensors. The position of the plume axis was found with the least squares method based on temperature measurements. A radius distance and angular position of each sensor in relation to the plume axis were determined. From the air velocity and temperature excess distributions above the simulator, integral parameters based on Gaussian parameters were calculated using equations suggested in [3] and listed in Table 1.

The set up was modified while performing measurements above the dummy and the manikin [10]. Simultaneous measurements of air velocity and temperature in the plume were performed at three heights above the head of the dummy and the thermal manikin in a sitting position. The arm with the velocity sensors and thermocouples was moved in steps of 0.1 m from the left side of the simulator to the right side. In this way, a rather dense measurement grid was achieved covering an area of 1.2×1.6 m above the simulator's head. Based on 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 determined based on equations listed in Table 1.

Table 1. Equations used to calculate integral parameters of thermal plumes.

Integral parameters	Cylinder and rectangular box	Dummy and manikin
Enthalpy flux	$Q = \pi \cdot \rho \cdot c_p \cdot \overline{w}_{zm} \cdot \Delta\bar{t}_m \cdot (R_t^2 \cdot R_w^2)/(R_t^2 + R_w^2)$	$Q = \rho \cdot c_p \sum (\Delta t_i \cdot w_i) \cdot \Delta s$
Volume flux	$V = \pi \cdot \overline{w}_{zm} \cdot R_w^2$	$V = \sum w_i \cdot \Delta s$
Buoyancy flux	$P = \pi \cdot \beta \cdot g \cdot \rho \cdot \Delta\bar{t}_m \cdot R_t^2$	$P = \rho \cdot g \cdot \beta \cdot \sum \Delta t_i \cdot \Delta s$
Momentum flux	$I = 0.5 \cdot \pi \cdot \rho \cdot \overline{w}_{zm}^2 \cdot R_w^2$	$I = \rho \cdot \sum w_i^2 \cdot \Delta s$

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

RESULTS AND DISCUSSION

The heated cylinder and rectangular box generate symmetrical thermal plumes with air temperature and velocity profiles of Gaussian distribution (Figure 3). It was expected that the average axis position above a cylinder would be in the middle of the vertical axis of the simulator but it was moved to the edge of the cylinder, which most probably was caused by a slight inhomogeneous condition in the chamber and in the upward free convection flow around the cylinder. This confirms that thermal plumes generated by heat sources of power similar to the human body are very sensitive to any cross flow as well as the boundary conditions of the convection flow at the heat source. Wandering of the plume axis above the cylinder from its average position was maximum ±6 cm on the x-axis and ±4 cm on the y-axis, while for the box it was maximum ±3 cm on the x-axis and ±5 cm on the y-axis.

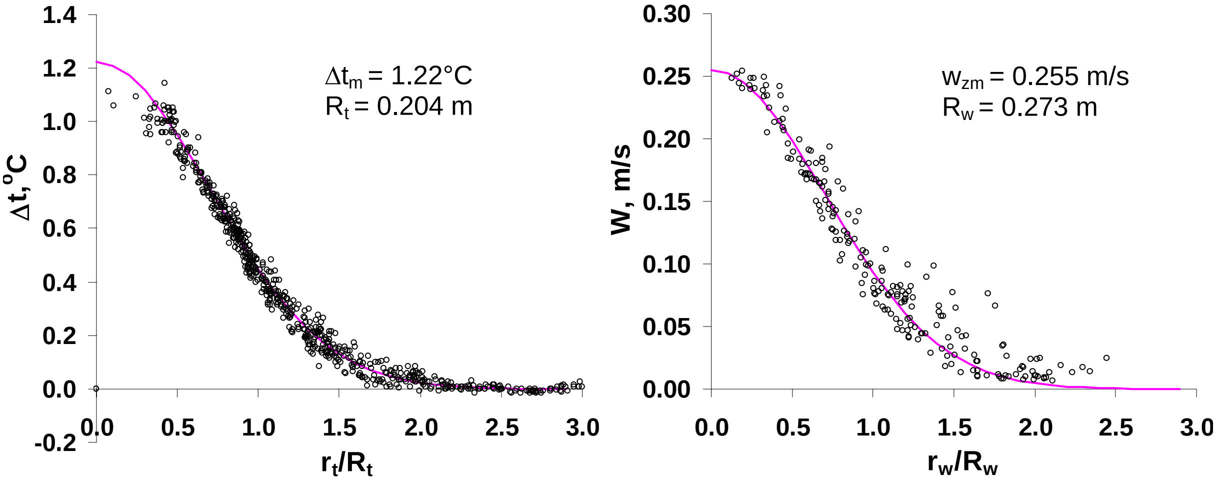

Figure 3. Temperature excess (left) and air velocity (right) profiles 0.7 m above the cylinder.

The thermal plumes above the dummy and the nude manikin are similar to each other. The plumes are not symmetrical because there is an impact of the thermal flow from the legs, so that the plume is always more to the front of the simulator. Therefore, a Gaussian distribution of the parameters can not be assumed. The convective flows above the dummy and the manikin are turned approx. 45 degrees to the left side of the room. Contours of constant air temperature and velocity in the thermal plume above the sitting nude manikin at the height of 0.7 m are shown in Figure 4.

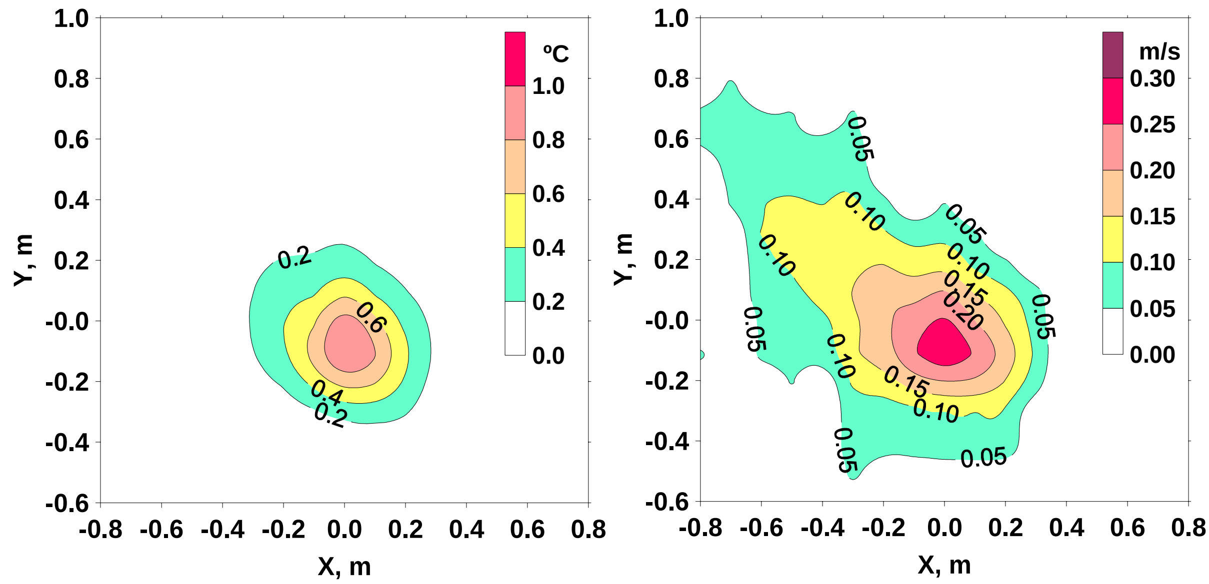

Figure 4. Maps of temperature excess (left) and air velocity (right) 0.7 m above the manikin.

Axis wandering was not significant for the plume generated by the dummy and the manikin since the position of the plume changed at most ±3 cm from the average position, so it was not taken into account.

Figure 5 presents the integral parameters, e.g. enthalpy flux Q, volume flux V, momentum flux I, and buoyancy flux P, for the cylinder, the rectangular box and the dummy divided by the respective parameters obtained for the thermal manikin, which has the closest shape to a real human body. The values of the integral parameters for the manikin were Q = 31 W, V = 0.0961 m^3/s, I = 0.0150 N, and P = 0.0065 kg/s^2. The volume and momentum fluxes of the plume above the cylinder and the rectangular box were lower, for the cylinder 60% and for the box 70% of the values obtained with the manikin. Enthalpy and buoyancy fluxes for both simulators are similar to the manikin. Plumes generated by these two simulators, especially the cylinder, are much narrower in comparison to the plumes above the dummy and the manikin. The plume generated by the rectangular simulator has the lowest ratio of temperature and velocity profiles widths (λ) - around 0.72, which means that the temperature profile width is around 28% narrower than the air velocity profile (Table 2). High values of the Archimedes's number (Ar), which presents the relation between the forces of buoyancy and inertia, in these cases, lead to the conclusion that a simple shape of simulators do not provide the necessary mixing in the plume.

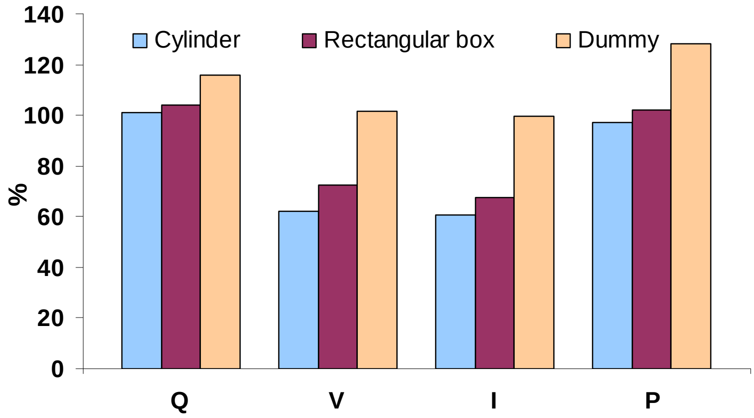

Figure 5. Ratio of the integral parameters of the plumes generated by the cylinder, the rectangular box and the dummy and the integral parameters of the plume generated by the manikin.

Much more comparable to the plume of the thermal manikin is the plume generated by the dummy, for which the integral and the Gaussian parameters are similar. The enthalpy flux and buoyancy flux are around 20% higher, while the two other parameters are almost the same (Figure 5). The more complex geometry the simulator had, the more intensive mixing was in the generated thermal flow, and the lower the Ar number was (Table 2).

Table 2. Gaussian and characteristic parameters [3] for the thermal plumes generated by the human body simulators.

No	Simulator	R_w	R_t	W_{zm}	Δt_m	Ar	λ
		m	m	m/s	°C		
1	Cylinder	0.273	0.204	0.255	1.22	0.170	0.747
2	Rectangular box	0.301	0.217	0.244	1.14	0.192	0.719
3	Dummy*	0.347	0.311	0.259	0.69	0.119	0.897
4	Thermal manikin*	0.337	0.282	0.269	0.67	0.103	0.838

* Gaussian parameters of an equivalent symmetrical thermal plume with the same enthalpy, volume, momentum and buoyancy fluxes as for the dummy or the manikin.

CONCLUSIONS

- Simulators of a sitting person with a too simple geometry, such as a cylinder and a rectangular box, generate much more concentrated plumes compared to simulators with a complex body shape and do not show a realistic situation from an air movement point of view. However, they can be used to simulate enthalpy and buoyancy fluxes.
- A dummy comprised of head, torso and legs can be successfully used as a simulator of a sitting person, especially when the air distribution in the room is considered.
- The results confirm that thermal plumes generated by heat sources with relatively low power are very sensitive to impact of the surroundings.

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