 #6326

A BREATHING MANIKIN FOR MEASURING LOCAL VENTILATION EFFECTIVENESS

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SUMMARY

The effectiveness of air distribution systems is usually studied in unoccupied test chambers. The heat loads from humans and equipment are simulated using various kinds of point or surface sources. This approach gives satisfactory results, when the whole room values of ventilation effectiveness are studied. It may, however, be less satisfactory in predicting the quality of air in the breathing zone. The local values are of great importance, in developing new systems for individual air distribution in workplaces. In this study, a heated manikin with artificial lungs was built and tested.

The manikin has 24 individual control circuits for the surface temperature, which is maintained at pre-defined values. A piston system is connected to the nose of the manikin to simulate breathing. The respiratory volume and rate can be adjusted. A tracer sampling point is situated at the tip of the nose. Local values of ventilation effectiveness parameters at this point can be measured .

The manikin was tested in a laboratory test chamber. There were significant differences in the local air exchange indicators in the test chamber. The best values outside the near-zone were found at the points located in the breathing zone. The use of a manikin did not have any significant effect on the air exchange efficiencies in the system studied. This was due to the fact that the heat load of the manikin was only 18 % of the total heat load. The local contaminant removal indicators were highly dependent on the placement and magnitudes of convective heat loads. The manikin could simultaneously be used for injection of tracer and sampling. In the injection, the tracer should either be released into the plume or through artificial lungs. By doing so, the tracer is mixed with the room air and will not drop to the floor due to buoyancy.

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INTRODUCTION

Being able to maintain an acceptable air quality in a restricted area of human occupancy and allowing lower air quality in other areas would lead to significant savings in terms of investments and energy costs. Displacement ventilation is a major step towards such savings. However, there is still much to be gained in the field of local ventilation systems.

Before new air distribution systems make their breakthrough, they must be thoroughly tested, first in laboratories, and later in actual field situations. The effectiveness of various air distribution systems is usually studied in unoccupied test chambers. The heat loads from humans and equipment are usually simulated using various kinds of point or surface sources. This approach gives satisfactory results, when the whole room values of ventilation effectiveness are studied. It may, however, be less satisfactory in predicting the quality of air in the breathing zone. The local values of ventilation effectiveness are of great relevance, in developing new systems for individual air distribution in workplaces.

In the case of displacement ventilation, the simulation of convective heat loads in the room is very important. In this study, a heated manikin with artificial lungs was built and tested. The manikin can simultaneously be used to measure local ventilation effectiveness and to evaluate of thermal comfort.

THE MANIKIN

The manikin is a male, size 50. It has 24 individual control circuits for surface temperature. The surface temperatures are maintained at pre-defined set-points using on-off control with 1 s control intervals. The set-points of each part of the body can be adjusted within the range of 31°C - 35°C.

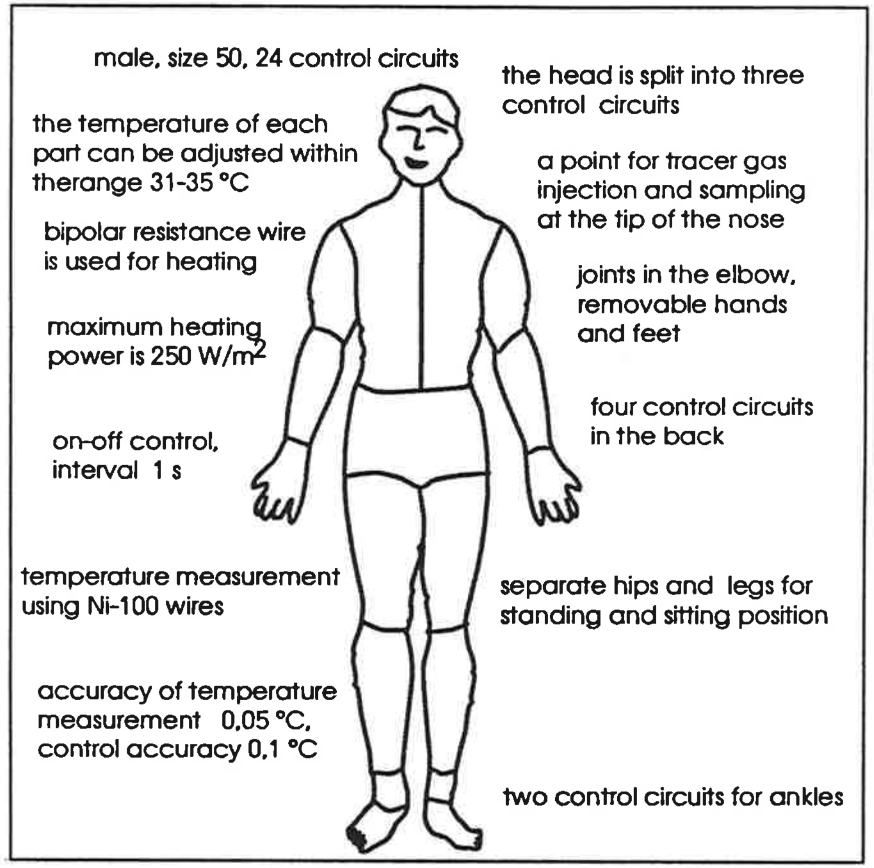

Fig. 1. The manikin.

A piston system is connected to the nose of the manikin to simulate breathing. The respiratory volume can be adjusted between 0-2 L. The breathing rate can be varied between 5-50 times per minute. Between 5 and 10 1/min, the motor runs at 10 1/min, while a magnetic clutch stops the piston movement for pre-defined intervals. A tracer injection tube can be connected to the breathing hose. A tracer sampling point is situated at the tip of the nose. This point is used to study the exposure to fresh air and contaminants. Local values of the ventilation effectiveness parameters can be measured using this point. A standard tracer gas instrument with a channel selector and two IR-analyzers is connected to the system. In the measurements described in this paper, carbon dioxide was used to simulate the movementsof the contaminant, and Refrigerant 12 was used to trace the fresh air.

MEASURING LOCAL VENTILATION EFFECTIVENESS

Basic Concepts

Ventilation effectiveness has two aspects: the ablity to deliver fresh air into the breathing zone, and the ability to remove contaminants from their place of origin. These two frameworks are needed because the flow pattern of fresh air is usually different from that of a contaminant. Our primary aim is to minimize human exposure to various contaminants. From this point of view, the contaminant removal effectiveness seems to be the appropriate tool for evaluating ventilation systems. However, each contaminant has different properties, which means that contaminant removal effectiveness can not be used as a universal measure of a system's ability to remove contaminants. The ability to deliver fresh air is of a more universal nature. In developing new air distribution products, it is more reasonable to evaluate the primary function, the delivery of fresh air, rather than the secondary function, the removal of contaminants, unless the properties of the contaminants in situ are known.

The Ability of a Ventilation System to Deliver Fresh Air

The concepts used while studying the short-term performance of the ventilation system are presented in the following. The nominal time constant (τ_n) is the volume of the ventilated zone divided by the rate of the fresh airflow to the zone. The nominal time constant is easily measured using the constant tracer emission or the tracer decay technique. The local age of air (τ_p) is the time it takes for the air molecule to travel from the air inlet to the studied point. The local age of air, which can be measured using the tracer decay technique, is the area under the decay curve divided by the initial concentration. The room mean age of air ($\langle\tau\rangle$) is the average of local ages of air. It can be calculated from the first moment of the concentration decay curve measured in the exhaust [1]. In measuring local and room mean ages, it is assumed that the airflow is constant during the measurement.

The air-exchange efficiency (ε_a) describes the replacement of room air with fresh air compared to an ideal (piston) flow pattern, and it is calculated as follows [2]:

$$\varepsilon_a=100*\tau_n/(2*\langle\tau\rangle), \tag{1}$$

where τ_n = nominal time constant, and $\langle\tau\rangle$ = room mean age of air.

The local air-exchange indicator (ε_i) is defined as the system's average nominal time constant divided by the local age of air at a point [3]:

$$\varepsilon_i=100*\tau_n/\tau_p \tag{2}$$

where τ_n = the system's average nominal time constant, and τ_p = the local age of air at a point.

The Ability of a Ventilation System to Remove Contaminants

Contaminant-removal effectiveness (ε) is the nominal time constant divided by the actual turnover time (the mean age of contaminants in the exhaust) [3]:

$$\varepsilon = 100 * \tau_n / \tau_t \tag{3}$$

where τ_n = the system's average nominal time constant, and τ_t = the turnover time of the contaminant.

With a constant airflow, Equation 3 can be expressed as follows [1]:

$$\varepsilon = 100 * C_e(\infty) / \langle C(\infty) \rangle \tag{4}$$

where $C_e(\infty)$ = the steady-state concentration in the exhaust, and $\langle C(\infty) \rangle$ = the volumetric average steady-state concentration in the system.

The local contaminant-removal indicator (ε_p) is defined as the system's steady-state concentration in the exhaust divided by the steady-state concentration at a point [3]:

$$\varepsilon_p = 100 * C_e(\infty) / C_p(\infty) \tag{5}$$

where $C_p(\infty)$ = the steady-state concentration at a point (room), and $C_e(\infty)$ = the steady-state concentration in the exhaust.

THE MEASUREMENTS

The Test Room

The measurement were made in a test room as shown in Fig. 2. The floor area of the test room is 16 m^2, the volume 42 m^3. A displacement ventilation system was used. The dimensions of the air inlet were 500 mm (w) x 1100 mm (h). Several heat loads were placed in the test room in order to simulate the cooling load. The total effect of these loads was approximately 30 W/m^2.

Two sets of measurements were made. In the first set, a standing manikin was used. The purpose of these measurements was to study the effects of the manikin on the whole room and local ventilation effectiveness. Table 1 shows the experimental set-up of these measurements.

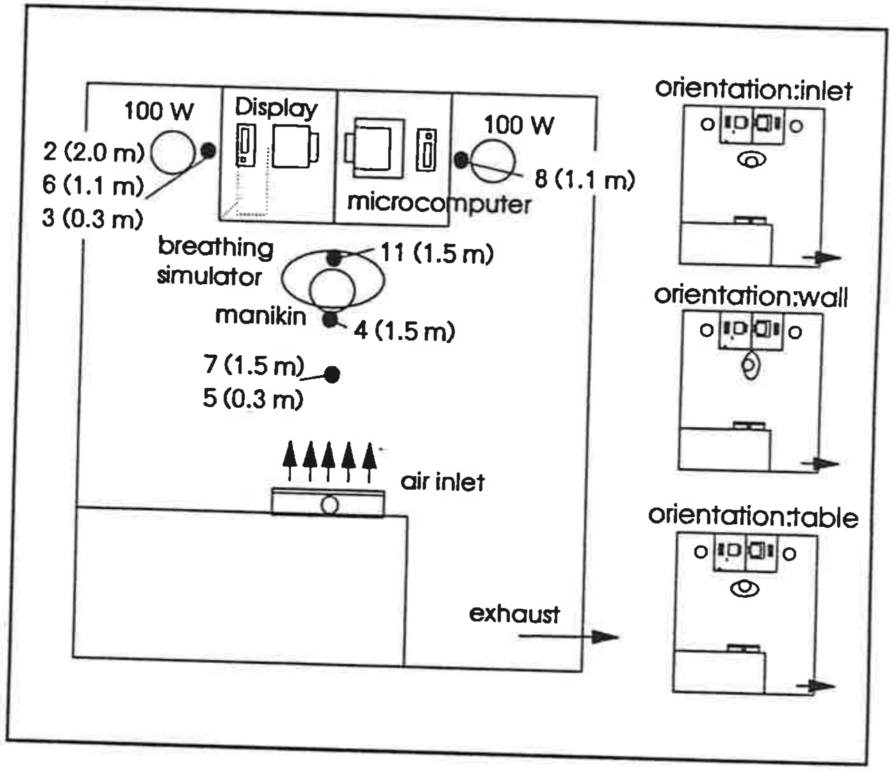

Fig. 2. The test room and the location of the instruments in the first set of measurements.

Table 1. The experimental set-up with a standing manikin.

Meas #	Orientation	Heating	Breathing	ΔT (K)	τ_n (h)	ε_a (%)
1.1	wall	ON	ON	4.2	0.20	56
1.2	wall	OFF	ON	4.1	0.21	56
1.3	wall	ON	OFF	4.7	0.22	58
1.4	inlet	ON	ON	4.1	0.22	58
1.5	inlet	OFF	ON	3.8	0.21	58
1.6	inlet	ON	OFF	4.2	0.21	57
1.7	inlet	OFF	OFF	3.8	0.21	58
1.8	table	ON	OFF	4.8	0.22	56
1.9	table	ON	OFF	4.5	0.21	55

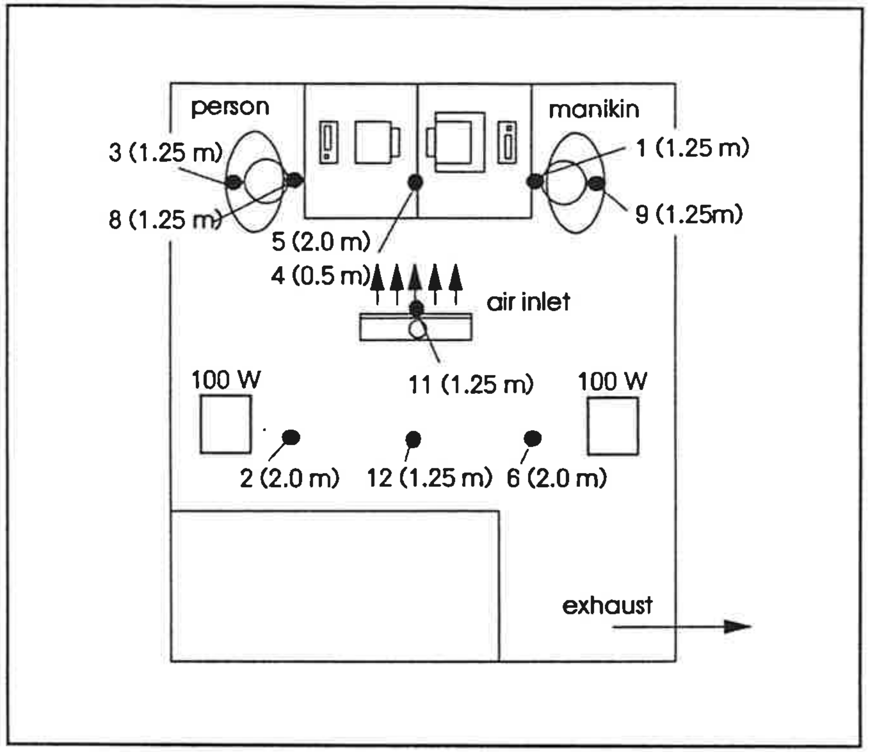

Fig. 3. The test room and the location of the instruments in the second set of measurements. Experimental design adapted from [4].

The second set of measurements was made using the manikin in sitting position. The main purpose of these measurements was to compare the local values of ventilation effectiveness with those of a test person.

Table 2. The experimental set-up with a sitting manikin and a test person.

Meas #	Test Person	Heating	Breathing	ΔT (K)	τ_n (h)	ε_a (%)
2.1	NO	ON	ON	4.1	0.25	68
2.2	YES	ON	ON*	4.1	0.17	53
2.3	YES	ON	ON*	2.8†	0.18	54

* No carbon dioxide injection.
†Heat loads on the table OFF.

THE EFFECTS OF THE MANIKIN ON THE FLOW FIELD IN THE ROOM

Air-Exchange Efficiency

The effect of the manikin on the air-exchange efficiency was studied in the first measurement set. The air-exchange efficiencies are shown in Table 1. The air-exchange efficiencies varied from 55% to 58%, average 57%, standard deviation 1.04%. Heating the manikin or using the breathing simulator did not have any significant effect on the global air-exchange efficiency in the test room. It should be noted that the total heat effect of the manikin, approximately 85 W, was relatively low compared with the total heat load in the test room. The heat loads in the measurements are, however, quite similar to those in a standard modern office room. If global ventilation effectiveness is our main interest, then these results indicate little advantage in using a manikin.

Local Air-Exchange Indicators

The local air-exchange indicators in the first set of measurements are shown in Table 3. A higher value means better air quality. It can be seen that fresh air flows from the near zone (point 5) fastest to the breathing zone of the manikin (points 11 and 4). However, there is only an insignificant difference between the nose of the manikin (point 4) and a reference point outside the plume of the manikin (point 7). For the standing manikin it seems that the fresh air passes the nose from the neck side. Smoke tests with a test person showed a similar phenomenom, but further measurements are needed to establish this. Movement and other disturbances may, of course, alter the situation.

Table 3. The effect using manikin on local air-exchange indicators.

Measurement Point	Heating ON Breathing ON	Heating ON Breathing OFF	Heating OFF Breathing ON
4 (nose)	0.94	0.98	0.88
11 (neck)	1.13	1.25	0.86
7 (reference)	0.84	0.86	0.82
5 (near zone)	1.40	1.45	1.37
2 (top left)	1.13	1.15	1.11
3 (mid left)	1.28	1.30	1.29
6 (bottom left)	1.01	1.12	1.14
8 (mid right)	0.81	0.89	0.93

The most notable effects on air quality are, obviously, found in the close proximity of the manikin. The simulation of breathing seems to work against the convective flow of the manikin. This may be due to the fact that the breathing air was at room, rather than body, temperature.

Points 6 and 8 lie symmetrically behind the manikin at the same height. It can be seen that fresh air flows better to point 6 than to point 8. This is probably due to the higher convective heat loads near point 6 (65% of the heat load was on the left side of the manikin). The use of the manikin slows down the entrainment of fresh air to a point behind the manikin (6 and 8).

Local Contaminant Removal Indicators

The local contaminant removal indicators in the first set of measurements are shown in Table 4. A higher value means better removal of contaminants and lower concentration. In the near zone (point 5), the local contaminant removal effectiveness is good, except for the case 'heating off, breathing off'. In that particular case the carbon dioxide, having 1.5 times the density of air, fell directly to the floor. In order to simulate the human emission of carbon dioxide, either a heated manikin or a breathing simulator should be used.

The manikin had a significant effect on the dispersion of contaminants within the test room. More studies are needed to establish the similarity between humans and the manikin. However, it is obvious that the instrument is needed in simulating the flow field of persons in a room.

Table 4. The effect of using manikin on local contaminant removal indicators.

Measurement Point	Heating ON Breathing ON	Heating ON Breathing OFF	Heating OFF Breathing ON	Heating OFF Breathing OFF
4 (nose)	0.60	0.29	0.97	0.87
11 (neck)	0.45	0.82	1.04	0.93
7 (reference)	1.04	0.89	1.05	0.94
5 (near zone)	1.54	1.16	1.57	0.48
2 (top left)	1.37	1.20	1.22	0.95
3 (mid left)	1.22	1.15	1.15	0.83
6 (bottom left)	1.21	1.08	1.11	0.84
8 (mid right)	1.06	1.29	0.74	1.04

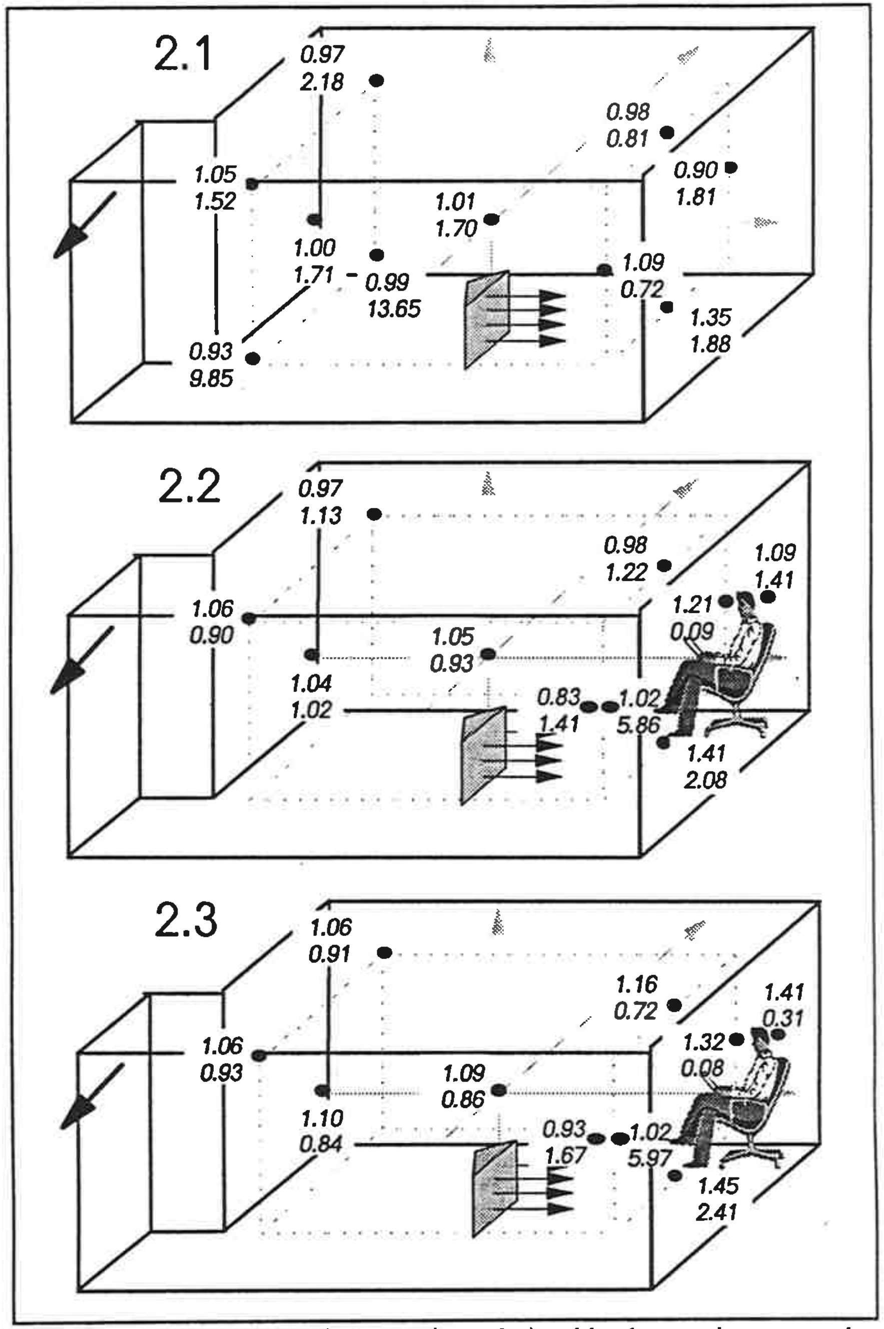

Fig. 4. The local air-exchange indicators (top value) and local contaminant removal indicators (bottom value) in the second set of measurements.

COMPARISON OF THE MANIKIN AND THE TEST PERSON

The local values of the ventilation effectiveness indicators in the second set of measurements are shown in Fig. 4. Measurement 2.1 is the reference case. It can be seen that the fresh air enters the manikin's breathing zone faster than the point without the manikin on the opposite side (1.09 h vs 0.90 h). The carbon dioxide spread from the manikin rises to ceiling level and into the exhaust.

In measurement 2.2, the heat load on the left-side chair was replaced with a test person. Should the convective flows on both sides now be equivalent, the local air-exchange indicators would have similar values. This is clearly not the case. The values on the right side (0.83 and 1.02) are somewhat lower than the values on the other side (1.21 and 1.09). The difference was even more significant in measurement 2.3, where the heat loads on the table were turned off. A more detailed look at the heat effect gives some explanation for this. The heat effect of the manikin was relatively constant, approximately 80-85 W. The heat effect of the test person ($M=58$ W/m^2, $A_{Du}=2.24$ m^2) was, however, calculated to be 130-140 W. The convective flow of the test person seems to override that of the manikin, and suck most of the fresh air.

The carbon dioxide exhaled by the test person rises to the ceiling level and flows to the exhaust. Due to the high convective effect, part of the flow runs down the opposite wall and deteriorates the quality of the air in the middle of the room (1.70 in meas. 2.1 vs. 0.93 and 0.86 in meas. 2.2 and 2.3), as well. The manikin's exposure to the contaminants released from another person in the room is negligible (5.86 and 5.97).

For a sitting person, the age of the air in the breathing zone (1.21, 1.09; and 1.32, 1.41) was almost as low as at the point 0.5 m above the floor in front of the inlet (1.41 and 1.45). There were no consistent differences between the face side and the neck side.

DISCUSSION

A breathing manikin was built and tested in a test room. The manikin could simultaneously be used for tracer injection and sampling. In the injection, the tracer should either be released into the plume or through artificial lungs. By doing so, the tracer is mixed with the room air and will not drop to the floor due to buoyancy.

In the displacement air distribution system studied, the manikin had significant effects on the local values. However, the manikin had little effect on the air-exchange efficiency of the whole room. This may be due to the fact that the manikin represented only 18 % of the total heat load in the room. Tests with the manikin and a test person showed that the convective flow of a person improves the quality of the air in the breathing zone when displacement ventilation is used. The results also point out the significance of correct simulation of the convective flows when studying local values. Further improvements are needed to produce more reliable simulations.

ACKNOWLEDGEMENTS

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