A STUDY OF THE AIR QUALITY IN THE BREATHING ZONE

A. Hatton[1], H.B. Awbi[2]
The University of Reading, Reading, UK.
[1]kcshaton@reading.ac.uk
[2]h.b.awbi@reading.ac.uk

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ABSTRACT

The paper deals with the differences in the air quality between that perceived by the occupants (breathing zone) and that in the occupied zone as a whole. An environmental chamber with a displacement ventilation system has been used to carry out the measurements with the presence of a heated mannequin and heat sources. Measurement of the age of air distribution in the chamber were carried out for different room loads. It has been found that the perceived air quality for a seated mannequin is about 40% better than the average value in the occupied zone. However, for a standing mannequin the difference is only about 10%.

INTRODUCTION

Displacement ventilation (DV) is widely used in mainland Europe and is also gaining popularity in the UK. In DV systems, the thermal plume from an occupant (body plume) influences the air movement whereby the cool air on the floor is entrained by the plume which then rises to the occupants head {Stymne et al. 1991}. As a result, the air quality at the breathing zone (the nose) is expected to be better than in other parts of the occupied zone {Brohus and Nielsen 1994}. Although a considerable amount of research work has been done on DV systems, there has not been any major study of the air quality at the breathing zone.

Current air movement design procedures focus on achieving an average air temperature and air quality index for the occupied zone without taking into consideration the effect of the thermal plume around the occupant's body and how this influences the occupant's perception of the indoor environment. If DV is to be widely accepted as a superior method of air distribution, it is essential that fundamental work be carried out to assess it's merits and limitations in terms of the perceived air quality and the range of air change rates within which the system does perform as a displacement system and not as a low level mixing system.

The paper presents measured local mean age of air, normalised age of air and temperature distribution for a number of points in an environmental chamber fitted with a DV system. Mean resultant velocity and temperature measurements are also presented. A heated mannequin, a heated box (to represent a computer and monitor), heated plates fixed to the wall of the chamber (to represent sun patches on the wall) and a fluorescent light represented the heat gain in the chamber. The heat sources were chosen to represent typical office equipment.

EXPERIMENTAL SET-UP

The chamber used for the experimental study has external dimensions 4.0m x 3.0m x 2.52m ceiling height, Fig. 1. It is constructed from panels made up of plywood, 100mm polystyrene board and a steel plastic coated plate (stelvatite). Floor joists support the chamber 300mm from the laboratory floor. The interior of the chamber comprises two compartments divided by a plywood partition. The refrigeration of the small compartment is provided by a compressor housed outside the chamber which is capable of cooling the compartment to -5°C and also heating it to 35°C if required by means of a cooling coil, fan and heater. The working compartment has interior dimensions 2.78m x 2.78m x 2.3m (ceiling height).

Four-wire Platinum Resistance Thermometer (PRT) sensors (accuracy = ±0.15K) have been used to measure the inside and outside surface temperatures of the chamber (Fig. 1). Other measuring devices used in the tests were an accurate Wattmeter, DANTEC omnidirectional velocity sensors and a Bruel and Kjaer SF_6 gas sampling system. The SF_6 gas analysis system incorporated a sampling box, gas analyser and a computer with the analysis and control software. The computer communicates with the measuring system and can be programmed to perform the gas sampling measurements.

The ventilation system that has been fitted to the chamber is an open system which draws air from the laboratory and exhausts the contaminated air out of the building. This is a push only system with a fan supplying the conditioned fresh air into the chamber and air leaves the chamber from a ceiling opening. In this set up air leakage from the laboratory is not a problem as the chamber is pressurised and well sealed. The ventilation system was well sealed and tested rigorously for leaks.

The fan draws the fresh air from the laboratory into the small compartment of the chamber. An air handling unit with an external compressor cools or heats the air to the desired setting for the inlet temperature. The air is then drawn into ducting in the small compartment and passes through a venturi for measuring the air flow rate.

The air is then supplied to the working compartment from a DV terminal unit fitted to the partition that divides the small compartment from the main working compartment, figure 2. The partition is insulated by a 50mm polystyrene board. The ceiling exhaust in the main compartment has a diameter of 100mm at a distance of 120mm from the partition on the ceiling centreline, see figure 3 a + b.

The DV unit used in these tests was of the flat type with 2mm diameter perforated holes. A total of 3,944 holes covered the surface of the DV unit. The total area of the openings was thus $0.0124m^2$, i.e. 5% of the area of the DV unit front face.

The heated mannequin used in the experiments (figure 4) was made from 1mm aluminium sheet which was chosen for its good thermal conductivity to allow an even distribution of temperature through the mannequin body. Heating elements inside the body, head and legs of the mannequin were controlled to provide the required temperature for each part.

The aluminium was cut and fashioned into a torso, neck, and the lower and upper leg portions. The head, however, was modelled from a wire mesh into the shape of a human head. A metal filler compound was used to coat the wire. This compound and the aluminium used had good thermal conduction properties. The nose was created from a piece of copper tubing with the metal compound used to model it into a nose shape. A polyurethane tube was attached to the copper tube inside the head and fed through the torso and out to the gas sampler. This location represented the sampling point for the breathing zone. Load was applied to the mannequin via resistance wire that lined the internal area of the whole mannequin. The heating load was varied with each test to keep the surface temperature of the mannequin equal to that of a typical naked human {Olesen 1982}. To keep the emmissivity of the surface close to that of human skin the mannequin was painted with mat beige paint.

To provide a realistic office situation a light, a computer and monitor, desk and a chair were placed in the chamber. Lighting was provided by a 36W fluorescent light, the computer and monitor were represented by a 400mm x 400mm x

400mm light box with a 150W light bulb fitted inside. The box was constructed from 1mm aluminium painted to increase the emmissivity of the surface to that equal to a computer. The desk and chair were standard office furniture. The desk was fitted with 3 drawers.

To investigate the conditions in the chamber with high heat loads, 2 heated plates were used to represent sun patches on wall 5, Fig. 3a. The heated plates were constructed from a 2mm sheet of polished aluminium, a 'Flexel' sheet heating element (≈1mm thick) and a 6mm thick panel of plywood. Holes of 6mm diameter were drilled into the aluminium to house the PRT sensors which were used to measure the surface temperature. Each plate had dimensions 1.01m x 0.52m wide.

MEASUREMENTS

The first priority in this work was to establish whether there is a difference between the perceived air quality and the air quality in the occupied zone. Therefore, the local mean age of air was required at a number of points in the room within the occupied zone and also at the breathing zone. Twelve sampling tubes were fixed at different points within the chamber. One point in the small compartment was used to sample the supply air. Any leakage of contaminated air could then be detected. As mentioned earlier, a sampling tube was fitted to the nose of the mannequin to sample the air at the breathing zone. Sampling tubes were fitted at the inlet and exhaust in the main compartment and a number of points in the occupied zone. The positions of these points are shown in figure 3 a + b.

The other end of the sampling tubes were connected to the SF_6 gas analysis system. Using the 'CDAS' software, the analyser and sampler were programmed to sample the gas at the specified sample points in the chamber.

To determine the local and mean age of air at the sampling points in the chamber, the tracer decay method was used. In this method, the tracer gas is dosed into the supply duct at a constant rate. The concentration of the gas was measured at selected sample points in the room and at the inlet. When the concentration at a selected point reached that of the inlet, the gas is turned off, this is time = 0, and the concentration at the selected sampling point is measured. To calculate the local age of air at the selected point, the area under the frequency distribution curve is divided by the initial concentration. Thus:

$$\bar{\tau}_p = \frac{\int_0^\infty C_p(t)\,dt}{C(0)} \qquad (1)$$

where $C_p(t)$ = Concentration at a point p at time t.

$C(0)$ = Concentration when the gas is turned off, time = 0

$\bar{\tau}_p$ = The local age of air at point p.

The mean age of air in the room can be obtained from the gas concentration in the extract duct by dividing the first moment of the frequency distribution curve by the area under the frequency distribution curve. The mean age of all the air present in the room can be calculated from:

$$\langle\bar{\tau}\rangle = \frac{\int_0^\infty t C_e(t)\,dt}{\int_0^\infty C_e(t)\,dt} \qquad (2)$$

where $C_e(t)$ =Concentration at the exhaust at time t.

$\langle\bar{\tau}\rangle$ =The room mean age of air.

The local and room mean age of air were calculated for all the sample points within the working compartment of the chamber (points 2 - 12) for each test condition. The data from these tests have been analysed and are presented in the results section.

Other measurements carried out during the tests were air temperatures and velocities. Dantec omnidirectional anemometers were used to measure the velocity and temperature at a number of points in the chamber. To compare the air temperature close to the ankle of the mannequin with the temperature close to the head of the mannequin sensors were fixed at heights of 0.10m and 1.1m close to the mannequin. These temperatures were checked against the recommended temperature gradient given in the international standard ISO 7730 {ISO 1984}.

The average velocity in the occupied zone should be below 0.15m/s to meet the ISO 7730 criteria for winter conditions or below 0.25m/s for summer conditions. Therefore a number of sensors were placed on a framework at several different heights in the occupied zone and also close to the front of the diffuser which were used to investigate the flow of air from the DV unit.

The measured internal and external surface temperatures of the chamber were used to calculate the conductive heat losses/gains from/to the chamber. Using the inlet and outlet temperatures and the air supply rate, the ventilation heat loss is calculated using:

$$Q_{vent} = \rho C_p \dot{v}\left(T_{in} - T_{out}\right) \quad (3)$$

where Q_{vent} =Load removed by ventilation (W)
ρ =Density of air (kg/m^3)
C_p =Specific heat capacity (J/kgK)
$\dot{v}$ =Flow rate (m^3/s)
T_{in} =Inlet temperature (°C)
T_{out} =Outlet temperature (°C)

PRT sensors were also used to measure the surface temperature of the heated mannequin, computer box and the heated plates. A number of air temperature PRT's were also used to measure the temperature at various points in the occupied zone. The Dantec velocity sensors were also able to measure temperature, so the data from these sensors were also included to provide a global distribution of air temperature distribution in the chamber.

TEST PROCEDURE

A number of test configurations have been investigated for this work with the emphasis on the air quality at the breathing zone of the heated mannequin in the chamber. Two scenarios were considered, the mannequin sitting and standing. This enabled the authors to investigate the difference in the perceived air quality for a seated or standing person. For each scenario, tests were carried out for a number of different loads, inlet temperature and flow rates. Listed in Table 1 are the configurations that were used. The room load was in the range 18 to 64W/m^2 floor area.

Table 1. Configurations tested.

Config. Number	Mannequin Posture	Air change rate (hour^{-1})	Total Load (W)	Heat components	Inlet Temp. (°C)
1	Seated	5	140	Mannequin, Light	20
2	Seated	5	300	Mannequin, Light, Box	18
3	Seated	5	392	Mannequin, Light, Box, Heated Plate	18
4	Seated	5	492	Mannequin, Light, Box, 2xHeated Plate	18
5	Seated	7	492	Mannequin, Light, Box, 2xHeated Plate	18
6	Standing	5	175	Mannequin, Light	20
7	Standing	5	310	Mannequin, Light, Box,	18
8	Standing	5	402	Mannequin, Light, Box, Heated Plate	18
9	Standing	5	502	Mannequin, Light, Box, 2xHeated Plate	18
10	Standing	7	502	Mannequin, Light, Box, 2xHeated Plate	18

RESULTS

From the tests with a seated and a standing mannequin, the mean age of air measurements at the 9 sampling points in the occupied zone have been averaged to obtain one value for the whole occupied zone of the chamber. For some of the results,. the local age of air has been normalised with respect to the mean age of air at the exhaust.

Figure 5 shows that the normalised age of air at the breathing zone of a seated mannequin is approximately 40% lower than that in the occupied zone. Generally the age of air can be seen to decrease with an increase in ventilation load for both the breathing zone and the occupied zone up to a load of about $30W/m^2$. Figure 6 shows that the local age of air changes with respect to ventilation load for a number of points in the room. At point 5, which is a point 0.5m from the DV unit and 0.6m above the floor, one can see the local age of air increases significantly at a ventilation load of 334W ($43W/m^2$). This is due to the high load and the low air supply temperature (18°C). The cool air from the DV unit drops to the floor quicker than in the other test configurations and misses point 5.

The data from figure 6 therefore shows that the changes in the room load effects the local age of air. However, changes in the ventilation load seem to have little effect on the local age of air at point 3. Point 3 is 0.5 m from the DV unit and 0.15m above the floor (see figure 3 (a + b)) and lies within the fresh air stream from the DV unit. Hence, ventilation load changes do not affect the air quality in the fresh air stream close to the DV unit.

From smoke tests, the air from the DV unit was found not to be uniformly distributed, as can be seen from figure 2. Therefore, one would except that the local age of air would be different at two points which are symmetrical with respect to the DV unit.

Configuration 5, where the air change rate is equal to 7 air changes/hour (2 air changes higher that configurations 1-4), seems to produce age of air results that are lower than for other configurations. This is probably due to the higher air change rate.

Figure 7 shows the normalised age of air for a standing mannequin at the breathing and occupied zones. Unlike that for a seated mannequin, there is very little difference here in the data for the occupied zone and that for the breathing zone. The average breathing zone data are only about 10% lower than that for the occupied zone. Also, there is little change in the age of air with increasing the room load.

In figure 8, like figure 6, one can see that changes in the ventilation load affect the local age of air at some points in the room. Again, at point 3 the changes in ventilation load have little effect on the local age of air. Furthermore, an increase in the air change rate decreased the local age of air at most points.

The results in the breathing zone for a seated and a standing mannequin are compared in figure 9. It can be seen that the age of air for a seated mannequin is lower than that for a standing mannequin. The probable reason is that the breathing zone for the seated mannequin is closer to the fresh air layer over the floor of the chamber.

Figure 10 shows that there is little difference in the age of air in the occupied zone when there is a seated or standing mannequin for in the chamber.

Figure 11 shows the temperature profile within the chamber for the seated mannequin test configurations. The point where the average wall temperatures lie on the lines for each test configuration denotes the neutral height. This figure shows that the neutral height for all but configuration 4 is close to the nasal height of 1.2m. However, the neutral height from the configuration 4 tests is somewhat lower at 0.9m. Therefore, for this test and because the cooling load is high there is more mixing in the room, i.e. the breathing zone is within the mixed flow region.

Figure 12 shows the temperature distribution within the chamber for the test configurations with a seated mannequin. The neutral height for all the configurations are below the nasal height of the standing mannequin (1.57m). Therefore, all the measurements at the breathing zone are within the recirculation zone. This would explain the difference between the breathing zone results for the two mannequin postures. In the upper recirculation zone the age of air increases more rapidly with height than in the lower displacement flow zone.

Table 2 shows the air temperatures in the room at 0.1m and 1.1m from the floor and also the mean velocity in the occupied zone. These are presented to confirm whether the room conditions agree with ISO standard 7730 recommendations for comfort. It is found that for test configurations 4 and 9 the temperature difference between 0.1m and 1.1m is higher than the temperature difference of 3K allowed by the standard. However, all the mean air velocities are found to be within both the winter and summer values for comfort. The difference between the total room load and the ventilation load is that lost by conduction. The maximum difference between the room load and the sum of the ventilation load and conduction is 10%.

Table 2. Measured ventilation load, air temperatures and mean air velocity in occupied zone.

Test Config.	Total Load (W/m^2)	Vent. Load (W/m^2)	Temp. at a height of 0.1m, (°C)	Temp. at a height of 1.1m, (°C)	Temp. difference K	Mean Air Velocity, (m/s)
1	18.1	12.9	24.9	24.87	-0.03	0.051
2	38.8	23.9	22.3	23.51	1.21	0.070
3	50.7	30.8	22.2	24.87	2.67	0.064
4	63.7	42.5	23.9	27.87	3.97	0.059
5	63.7	47.7	22.5	25.5	3.0	0.059
6	22.6	19.8	23.0	23.63	0.63	0.039
7	40.1	33.1	25.2	25.02	-0.18	0.033
8	52	37.87	23	25.67	2.67	0.05
9	64.9	42.6	23.7	27.48	3.78	0.059
10	64.9	49.1	22.9	25.19	2.29	0.073

CONCLUSIONS

This paper investigates the differences between the air quality at the breathing zone with that in the occupied zone for different room loads and air change rate. An office type room load scenario was considered using displacement ventilation. A heated mannequin was used to represent a person.

One can conclude from the results that:

1. The perceived (breathing zone) air quality for a seated mannequin is ~40% better than the average air quality in the occupied zone.
2. The perceived air quality for a standing mannequin is ~10% better than the average air quality in the occupied zone.
3. The average perceived air quality for a seated mannequin is ~40 % better than that for a standing mannequin.
4. The air quality in the occupied zone is almost unaffected by the posture of the mannequin in the chamber.
5. For conditions with a ventilation load above 328W ($42W/m^2$) and an air change rate of 5 ac/hour the temperature difference between 0.1 and 1.1m heights was higher than that recommended by ISO 7730. Higher ventilation loads could be achieved that were within the ISO standard by increasing the air change rate to 7ac/hour.

ACKNOWLEDGEMENTS

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FIGURES

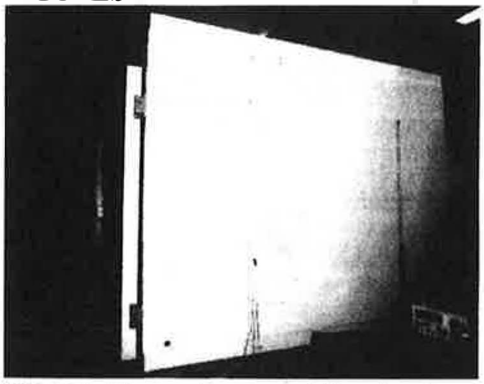

Figure 1. The environmental chamber.

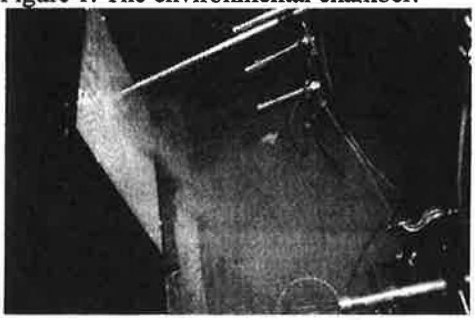

Figure 2 Photo of DV unit fitted to the partition wall in the chamber.

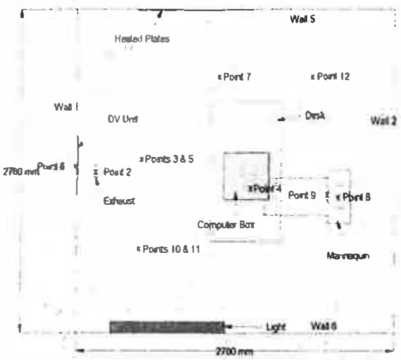

Figure 3a. Plan view of the working compartment with the gas sampling point locations. Point 9 is at the breathing zone.

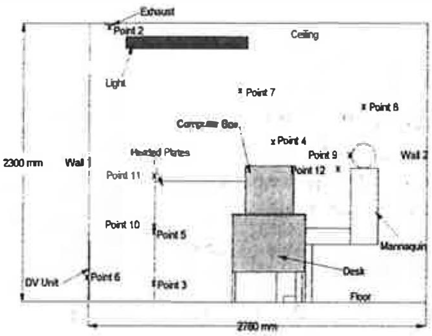

Figure 3b. Plan view of the working compartment with the gas sampling point locations. Point 9 is at the breathing zone.

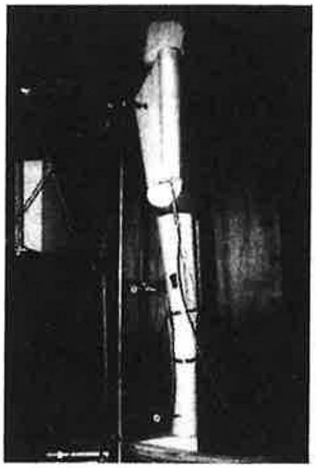

Figure 4 The heated mannequin.

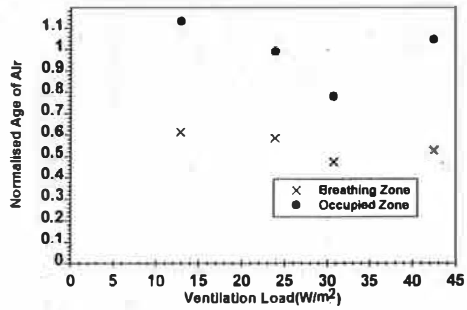

Figure 5. Normalised age of air for a seated mannequin.

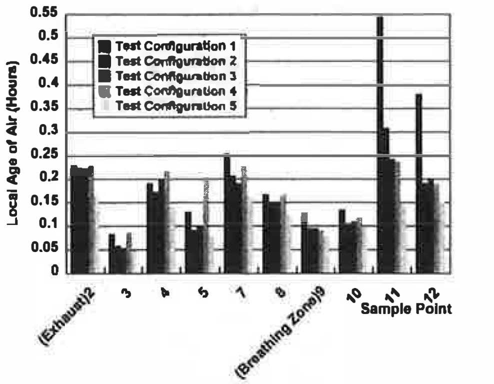

Figure 6. Local age of air for a seated mannequin.

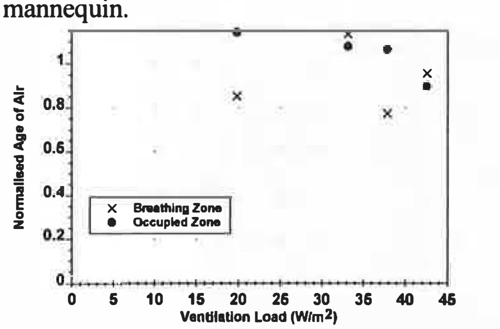

Figure 7. Normalised age of air for a standing mannequin.

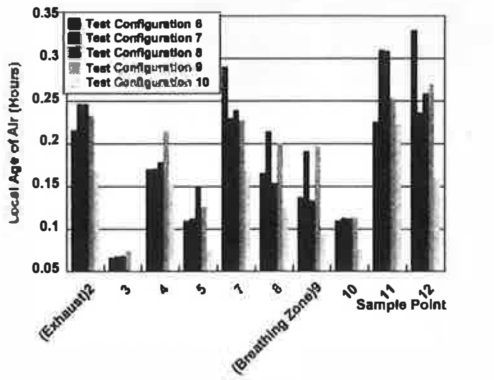

Figure 8. Local age of air for a standing mannequin.

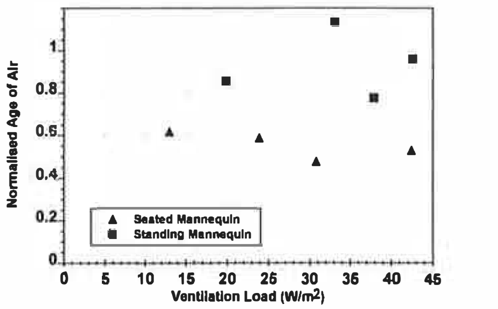

Figure 9. Normalised age of air at the breathing zone.

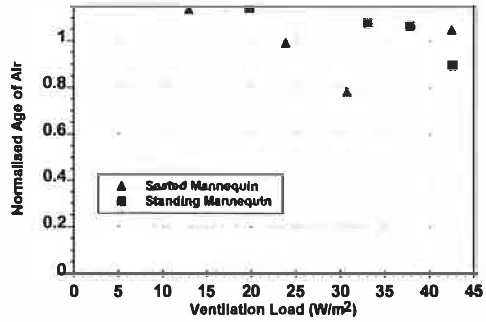

Figure 10. Normalised age of air in the occupied zone.

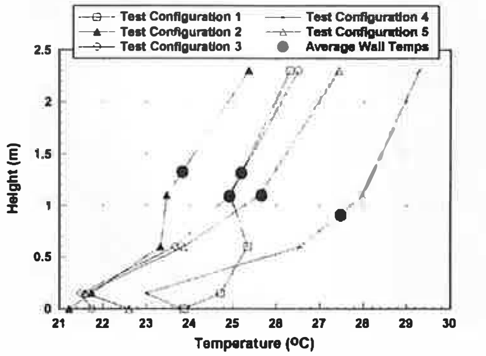

Figure 11. Temperature results for a seated mannequin.

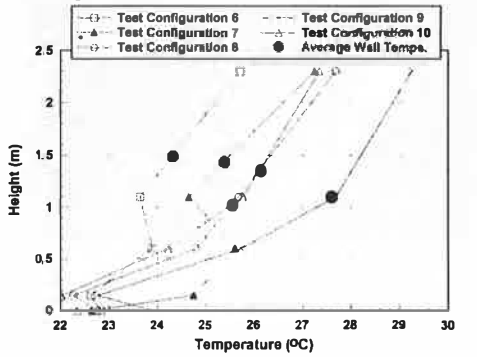

Figure 12. Temperature results for a standing mannequin.