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Airflow Around a Passenger Seated in a Bus

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The thermal comfort conditions perceived by the occupants of a bus during a typical summer are evaluated through the mapping of the flow field in the zone occupied by passengers, in terms of mean air velocity, turbulence intensity, and temperature.

A full scale bus section was used in laboratory tests, with the passenger presence simulated by a thermally-regulated mannequin and the solar radiation by a panel of lamps with a spectrum similar to that of the sun. Given the symmetry of the vehicle, the only situations reproduced were those where the vehicle was subjected to radiation from the left-hand side.

Measurements were performed both with and without a passenger seated in the window seat and in the aisle seat. In each case, two situations were considered, one with the solar protection curtains up and the other with them down.

INTRODUCTION

Thermal comfort in passenger buses is an important requirement for both users and designers. Usually, thermal comfort can be obtained using heating systems, cooling systems and/or forced air systems, that are installed in the buses. The comfort conditions for an indoor situation are established by ventilation standards, namely ISO 7730, ASHRAE 55-1992 and more recently by CENprENV 1752.

The thermal comfort depends on two individual parameters (the clothing level and the activity level) and on four ambient parameters (the mean air temperature, the mean radiant temperature, the mean air velocity and the relative humidity in the air). Fanger (1972) developed a general equation for thermal comfort, using these six parameters, with the aim of estimating acceptable thermal comfort conditions. This theory, presented also in ISO 7730, introduced two new indices: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). For acceptable thermal comfort conditions the PMV changes within a range of ± 0.5 (PPD $<$ 10%).

Thermal comfort in vehicles has been studied by Olesen (1989) and Olesen and Rosendahl (1990). However, if good knowledge of the air distribution is required as a step to the development of a new design or to improve an existing one, the velocity field in the studied domain should be well know. Some examples of this kind of study can be found in Temming and Hucho (1979), Han (1989), and Klemp et al. (1991). Asakai and Sakai (1974), Chang and Gonzalez (1993), and Melikov et al. (1994) analyzed the flow around the occupants in detail.

The objective of this study was to characterize the flow field around bus passengers and to evaluate the thermal comfort conditions perceived by the occupants of this kind of vehicle. The work was done using a full scale bus section, in the laboratory. A Summer situation was reproduced, in which the bus was subjected to the solar radiation from the left side.

EXPERIMENTAL SETUP

The measurements were carried out using a full-scale sectional module of the passenger compartment of an intercity bus. The module was 2 m long, with two rows of seats, and was built

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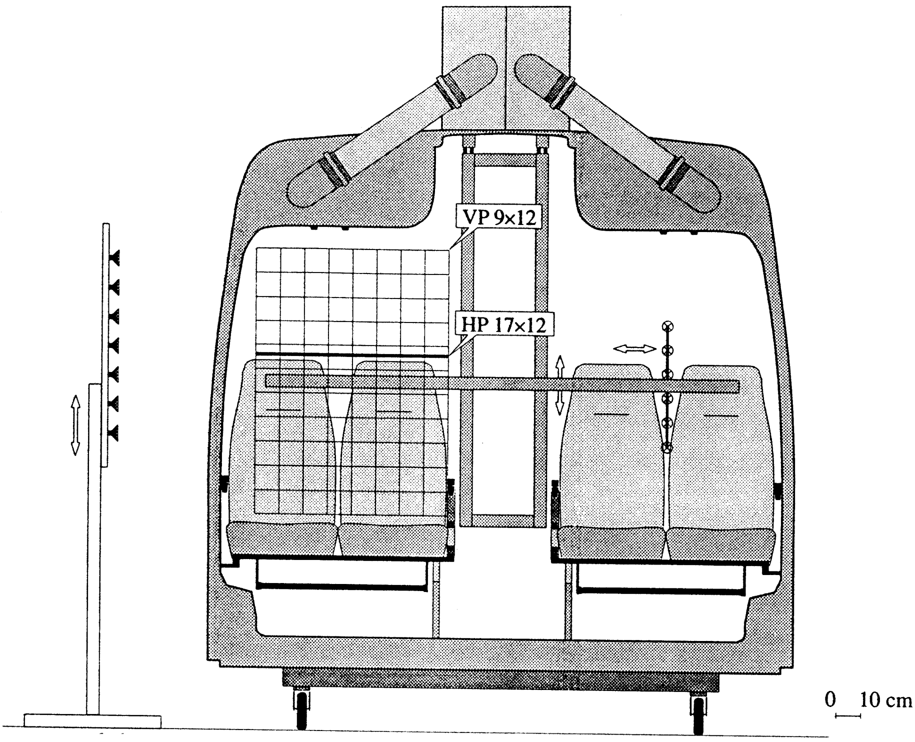

Figure 1. Full scale bus laboratory section

with all the construction details of a real bus (Figure 1). Air was introduced in the compartment through nozzles placed in the ducts over the seats.

An air conditioner and two centrifugal fans of the type commonly used in the automotive industry, driven by DC Motors, were used to blow air into the ducts. The air conditioner was placed above the module structure. It had a maximum power of 4410 W (heating and cooling) and a maximum air flow of 570 m^3/h. During these tests the air at the nozzle exits had a constant temperature of 19°C. The power supply of the DC motors was regulated in order to obtain an air velocity of 6 m/s at the outlet, which was in the order of the mean value measured in a real bus. Particular care was taken with the duct system in order to have the same conditions in the various jets and to ensure the flow symmetry in the passenger compartment.

The sun was simulated by a group of 28 dichroic lamps, each with a power of 150 W. The radiation in the windows surface was almost uniform, with an intensity of 700 W/m^2, which is approximately the maximum radiation on a vertical surface during a typical summer day (in a temperate climate).

"Maria", the thermal-mannequin used to simulate the presence of a passenger, was 1.68 m tall and divided in 16 sections. The mannequin was made at the Technical University of Denmark (Madsen et al. 1986). The skin temperature of each section was uniform and similar to that of a standard person in thermal comfort (32–37°C, depending on the section). A more detailed description of test conditions concerning the mannequin can be found in Conceição et al (1996)

Air temperature and air velocity measurements were performed with a multichannel flow analyzer. A comb-shaped device was used, comprising six probes, equally spaced along a line, at 100 mm intervals. This was connected to a manual three-axes traversing mechanism. Different

Table 1. Nomenclature of Measuring Planes

	Curtains			
	Up (U)		Down (D)	
	Measuring Plane Location			
Mannequin	**Horizontal (H)**	**Vertical (V)**	**Horizontal (H)**	**Vertical (V)**
Absent	**AUH**	**AUV**	**ADH**	**ADV**
	Side (S)	Frontal (F)	Side (S)	Frontal (F)
Corridor seat	**CUS**	**CUF**	**CDS**	**CDF**
Window seat	**WUS**	**WUF**	**WDS**	**WDF**

measuring planes were mapped inside the bus module, in terms of velocity, turbulence intensity, and temperature.

Three possibilities were considered, with respect to the positioning of the passenger: (1) absent, (2) seated beside the window, or (3) seated in the aisle seat. In each one of these situations, the solar protection curtains were placed first up and then down. Because two measuring planes were mapped in each case, a total of 12 planes were covered, as described in Table 1.

The measuring grids, considered for situations AUH, AUV, ADH and ADV, are shown in the Figure 1. Measurements were performed in two grids, one vertical with 9 × 12 points, at 100 mm intervals, and one horizontal, with 17 × 12 points, at 50 mm intervals. The first one contained the two jets axes and started just below the nozzle exits. The second was in a horizontal plane, placed 1.1 m above the floor level, in the passengers breathing area (i.e. near the head).

The measuring grids used for the other situations are depicted in the Figures 2 and 3. All these grids were vertical with intervals of 5 cm between points. Two grids were used, one just in front of the mannequin, in a longitudinal plane, and another over the empty seat beside the mannequin, in a transversal plane.

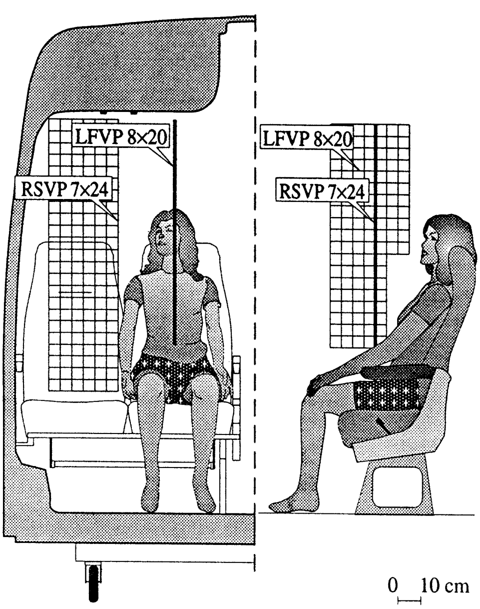

Figure 2. Measuring planes when passenger seated in corridor seat

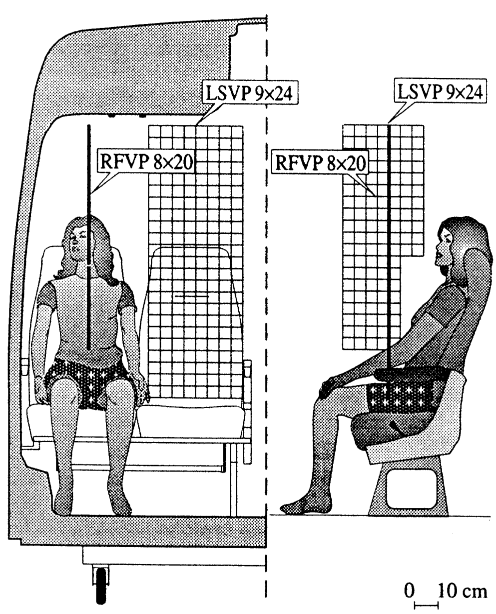

Figure 3. Measuring planes when passenger seated in window seat

RESULTS AND DISCUSSION

The isoline maps for situations AUH, AUV, ADH and ADV are depicted in Figures 4–7 for vertical planes and in Figures 8–11 for horizontal planes. The sequence of presentation, in each case, is air velocity, air temperature, turbulence intensity, and PPD values.

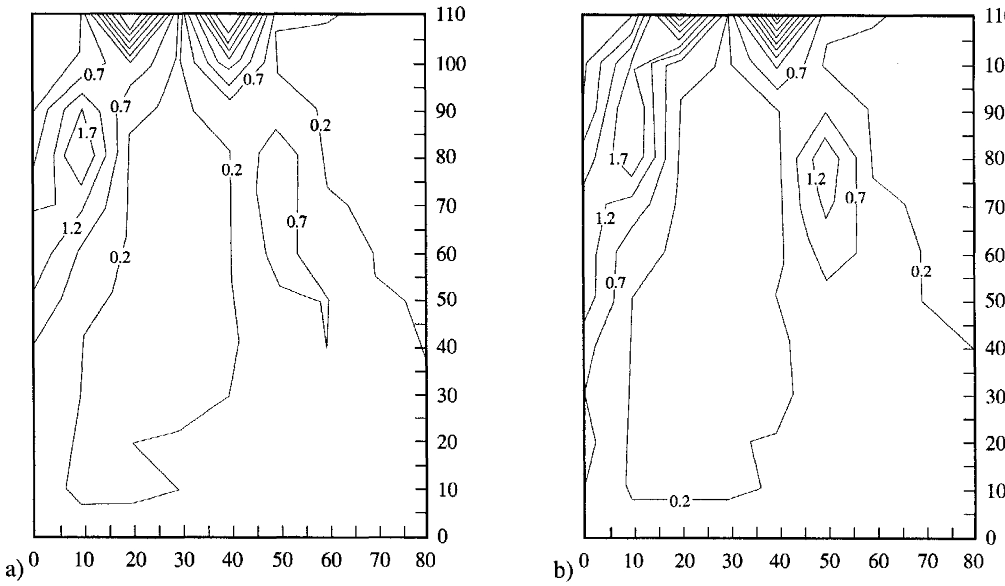

Figure 4. Vertical plane (VP 9 × 12) velocity isolines (m/s) for cases (a) AUV and (b) ADV

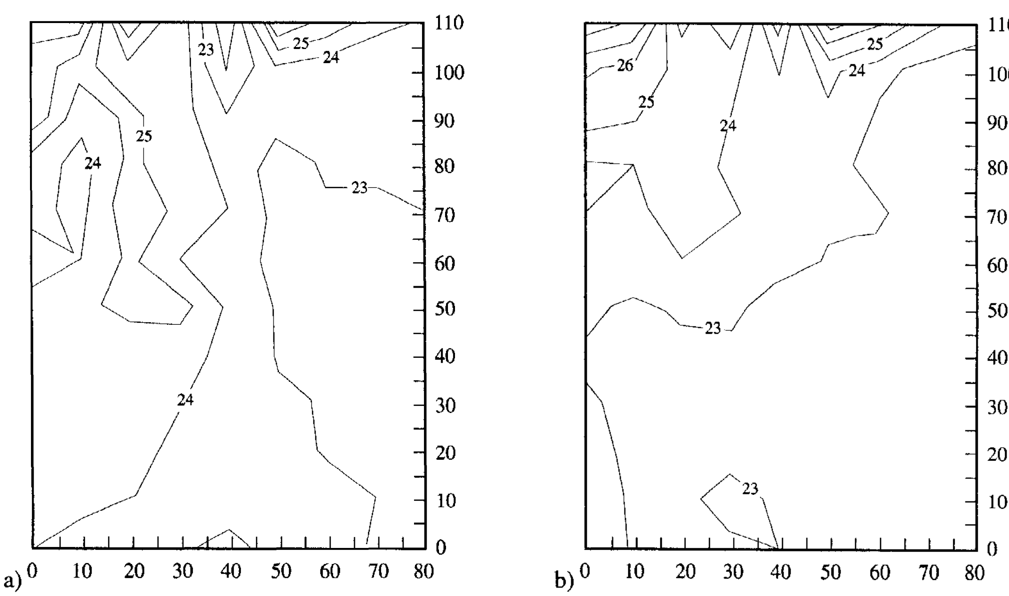

Figure 5. Vertical plane (VP 9 × 12) temperature isolines (°C) for cases (a) AUV and (b) ADV

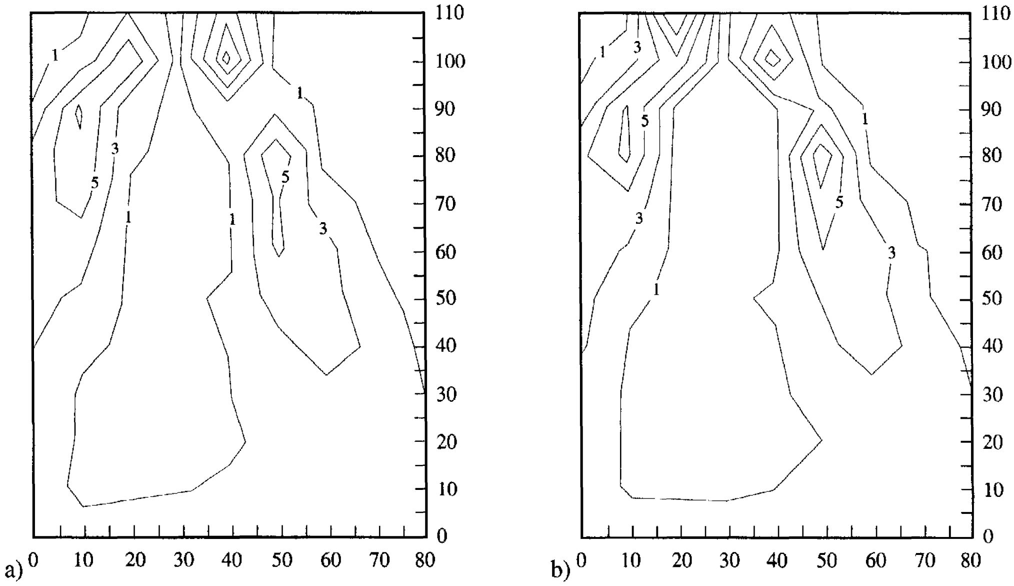

Figure 6. Vertical plane (VP 9 × 12) turbulence intensity isolines (%) for cases (a) AUV and (b) ADV

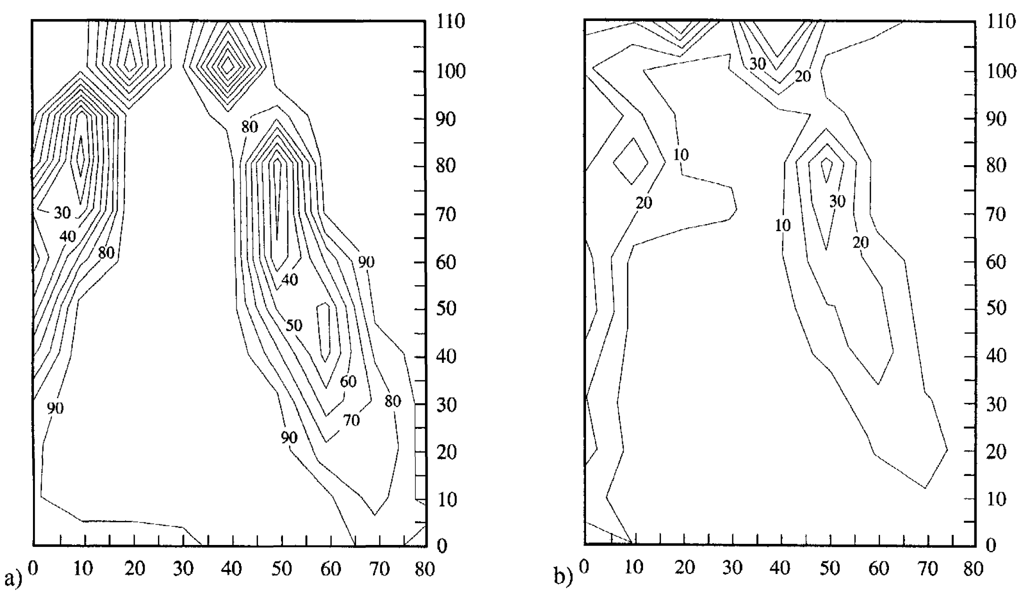

Figure 7. Vertical plane (VP 9 × 12) PPD isolines (%) for cases (a) AUV and (b) ADV

The turbulence intensity values were obtained, at each point, by dividing the standard deviation of local velocity fluctuations by a reference velocity, corresponding to the initial velocity of the jets. This procedure was adopted because it resulted in more physically meaningful graphics than those obtained if the local mean velocity was used as the designator. Quite large turbulence values appeared in the points with almost zero velocity, if the common expression was used.

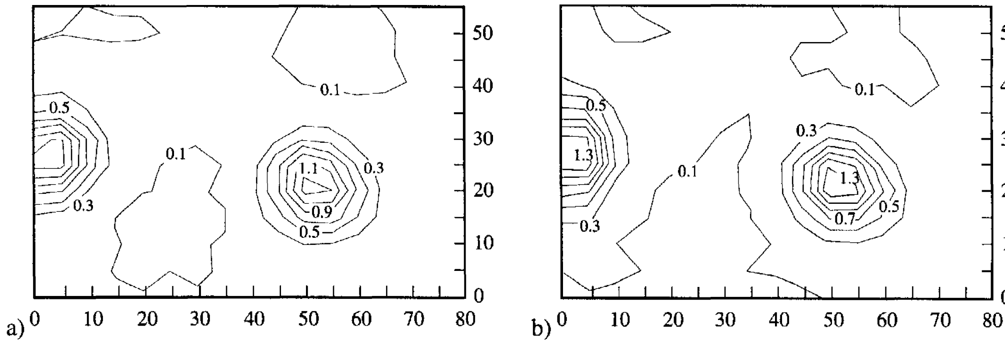

Figure 8. Horizontal plane (HP 17× 12) velocity isolines (m/s) for cases (a) AUH and (b) ADH

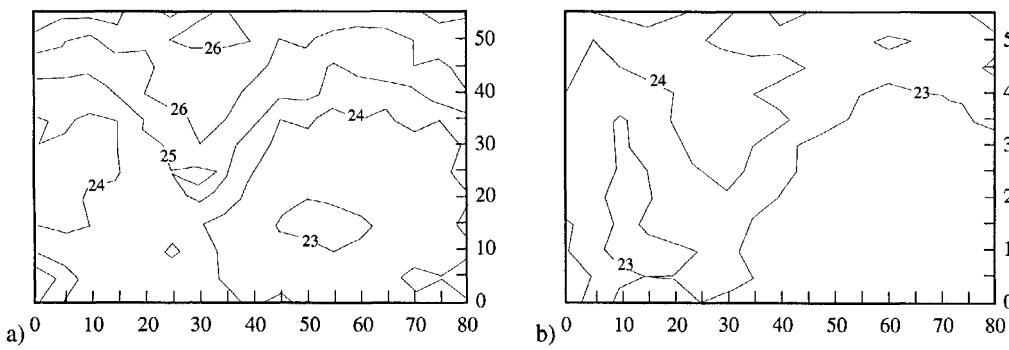

Figure 9. Horizontal plane (HP 17× 12) temperature isolines (°C) for cases (a) AUH and (b) ADH

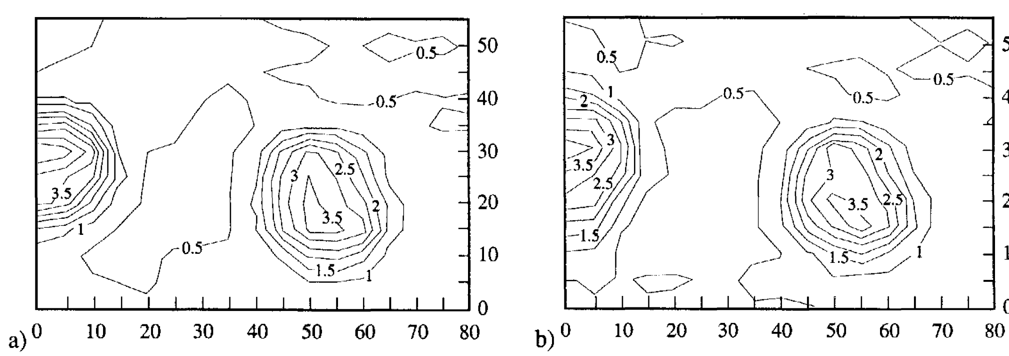

Figure 10. Horizontal plane (HP 17× 12) turbulence intensity isolines for cases (a) AUH and (b) ADH

At each point of the measuring grids, the PPD values were calculated using the measured values of air velocity and temperature in the thermal comfort equation presented in ISO 1730. In the calculation the following values were considered: activity level = 1 met, clothing insulation value = 0.7 clo, water vapor pressure = 1500 Pa, mean radiant temperature = 46°C (curtains up) and 29°C (curtains down). The assumed values for the mean radiant temperature inside the module resulted from some preliminary measurements performed with an indoor climate analyser.

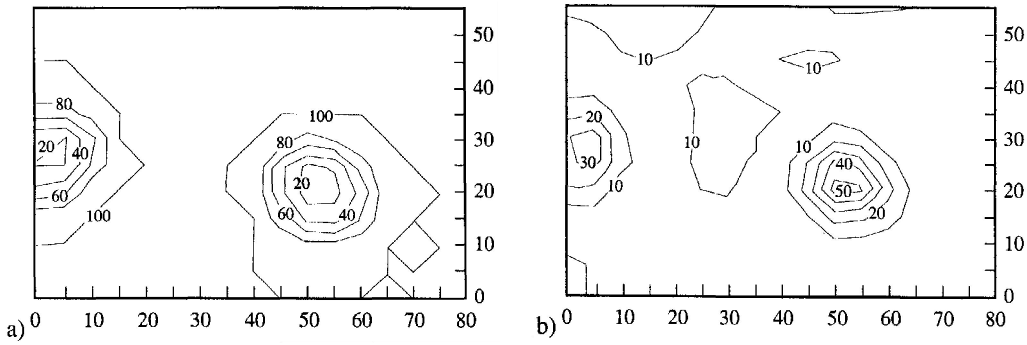

Figure 11. Horizontal plane (HP 17× 12) PPD isolines (%) for cases (a) AUH and (b) ADH

In all situations studied, most of the occupied zones had air velocities between 0.2 and 0.7 m/s. Only a very localized peak, over 0.7 m/s, occurred in the jet core region at the level of the passenger's head.

The flow topology is similar in cases AUV and ADV. However, a difference in the behavior of the jet beside the window can be found in each of the two situations. The jet strikes the window at an upper level when the curtains are up, presumably because of the opposition of the upward buoyancy flow induced by the window's hot surface.

The air temperature values were slightly higher with the curtains up than with the curtains down. However, the discrepancies found in PPD values were much more due to the differences in the radiant rather than the air temperature.

In the occupied zone, PPD values when the curtains were raised were in a range from 50% to 100% with positive PMV values. This condition corresponds to a hot, uncomfortable ambient temperature. On the other hand, when curtains were down, the conditions in most of the occupied zone were comfortable, with very localized areas where PPD exceeded 20%. The higher PPD values occurring in this situation derived from negative PMV values, corresponding to a draft sensation caused by the higher velocity zones of the jets.

The remaining figures (Figures 12 through 19) illustrate the measurements obtained with the passenger presence simulated by the thermal mannequin. Figures 12–15 correspond to planes CUS, CUF, CDS, and CDF when the passenger was seated in the aisle seat. Figures 16–19 are related to WUS, WUF, WDS, and WDF when the passenger was in the window seat. The three maps in each figure show (a) velocity, (b) temperature, and (c) for turbulence intensity.

The resulting comparative analysis of the figures are summarized as follows:

- Air velocity isolines in the CUS and CUF planes showed no significant difference when compared with the isolines obtained in the absence of the mannequin/passenger. The striking area of the jet on the left side was still in the upper level when the curtains were raised, as was previously verified.
- The presence of the passenger in aisle seat induced a non-depreciable increase of the temperature level in the adjacent plane (i.e. the unoccupied seat beside the mannequin), mainly when the curtains were raised. In the CUS plane, the observed temperatures in the occupied zone, ranged from 27 to 28°C, whereas in the absence of a passenger, values between 23 and 25°C were measured.

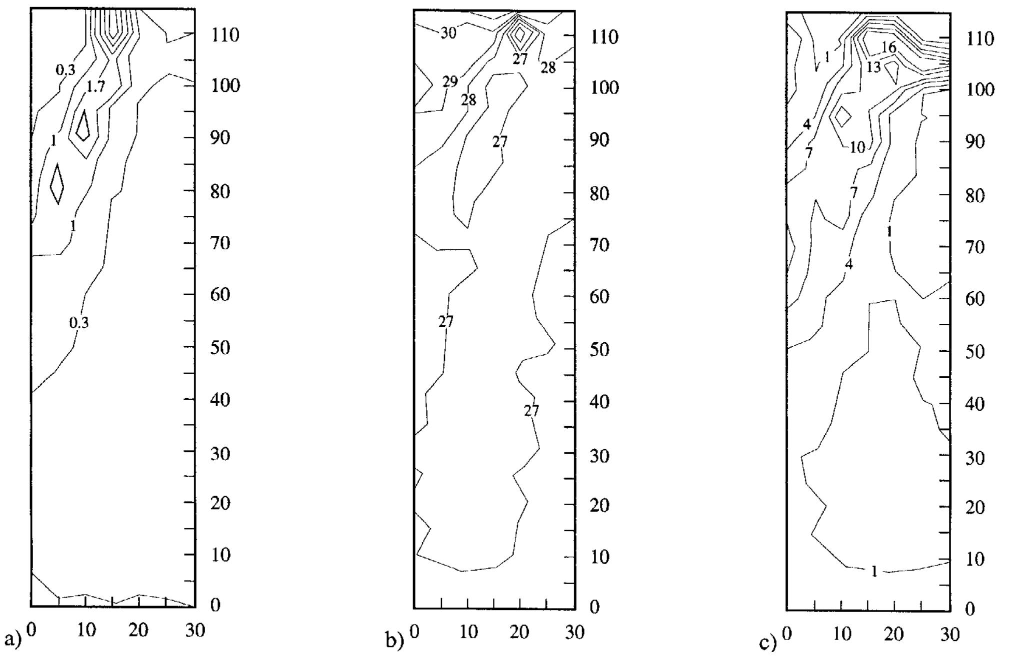

Figure 12. Vertical plane (RSVP 7 × 24) CUS case
a) Velocity, b) temperature, and c) turbulence intensity isolines

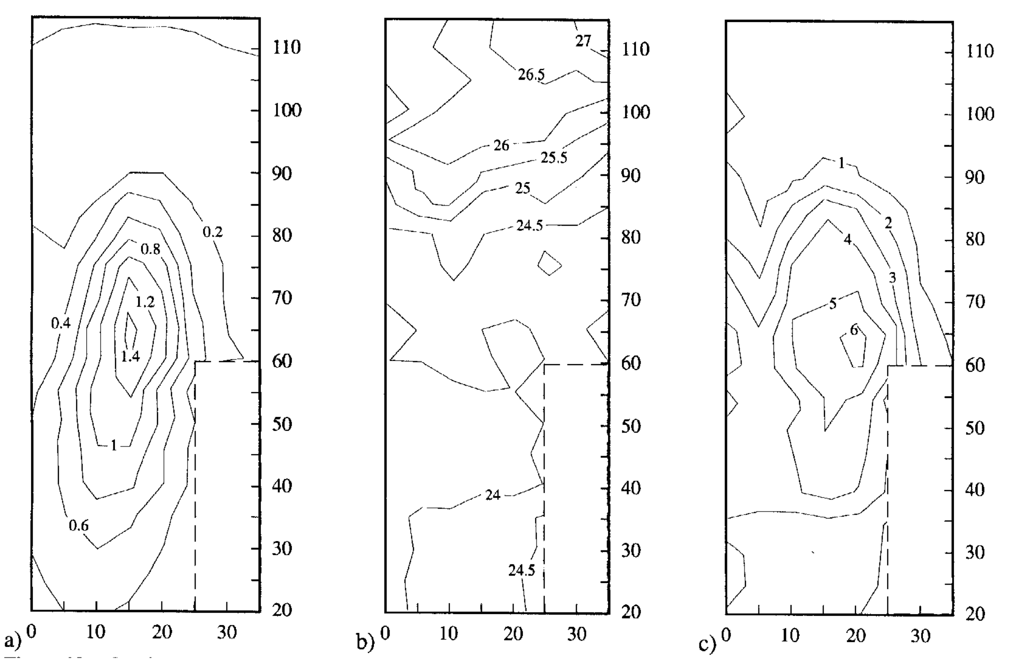

Figure 13. Vertical plane (LFVP 8 × 20) CUF case
a) Velocity, b) temperature, and c) turbulence intensity isolines

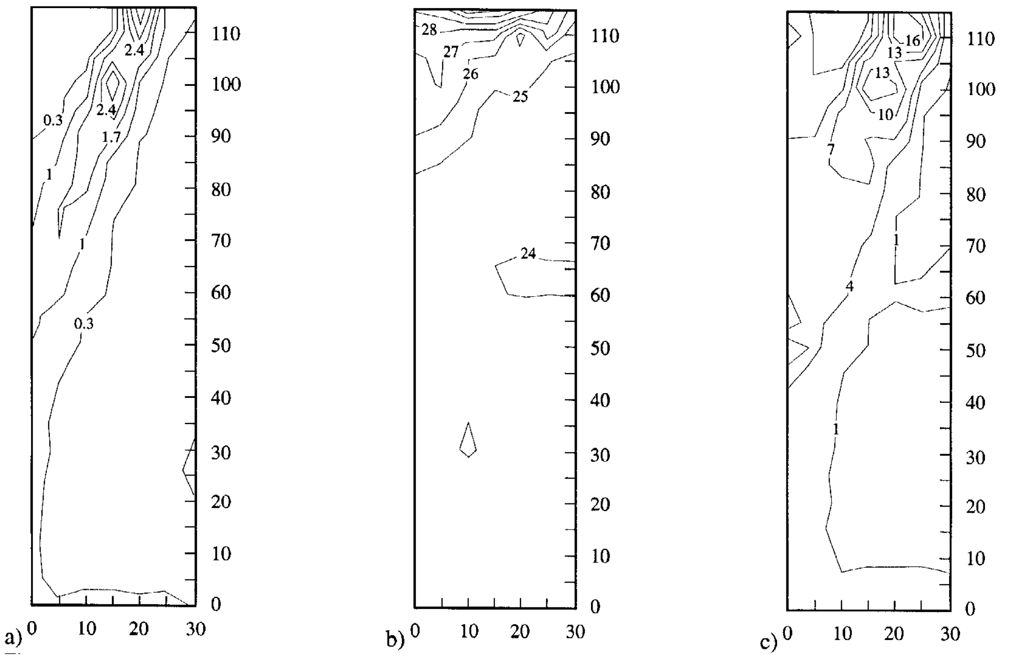

Figure 14. Vertical plane (RSVP 7 × 24) CDS case
a) Velocity, b) temperature, and c) turbulence intensity isolines

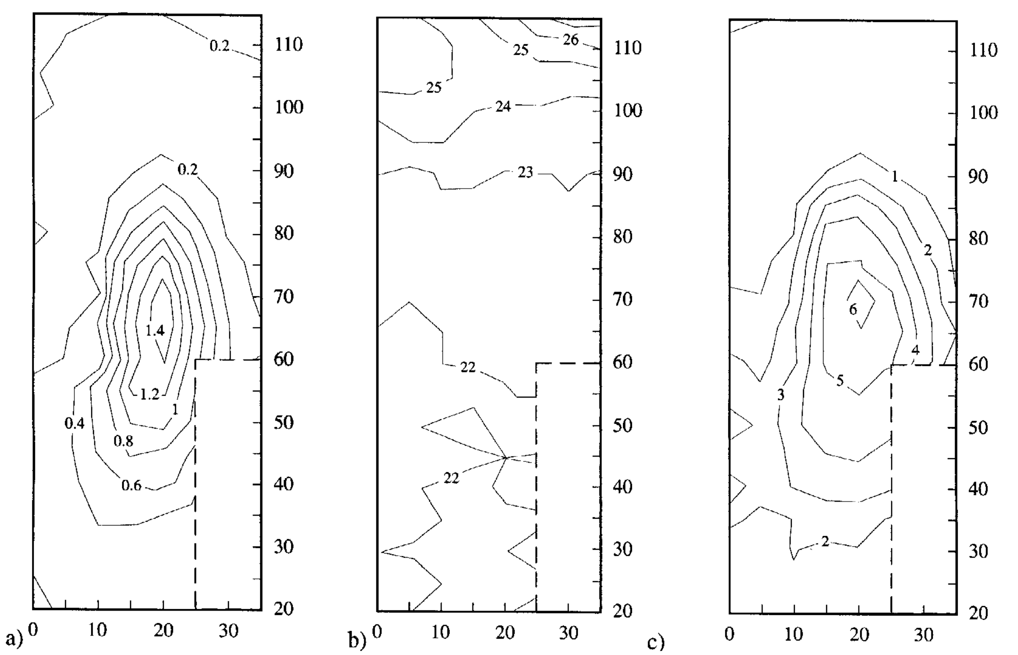

Figure 15. Vertical plane (LFVP 8 × 20) CDF case
a) Velocity, b) temperature, and c) turbulence intensity isolines

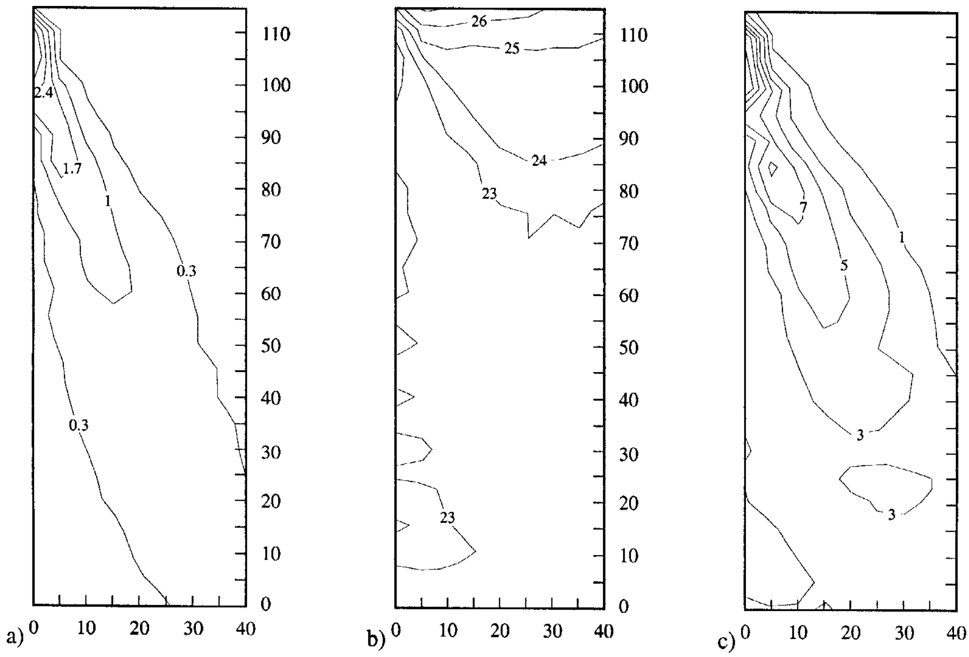

Figure 16. Vertical plane (LSVP 9 × 24) WUS case
a) Velocity, b) temperature, and c) turbulence intensity isolines

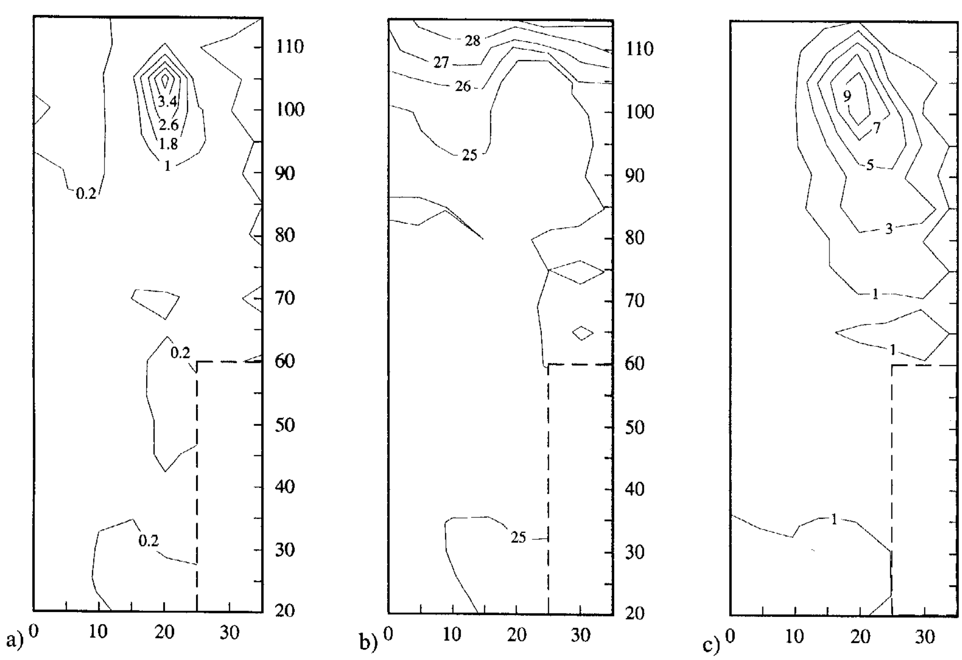

Figure 17. Vertical plane (RFVP 8 × 20) WUF case
a) Velocity, b) temperature, and c) turbulence intensity isolines

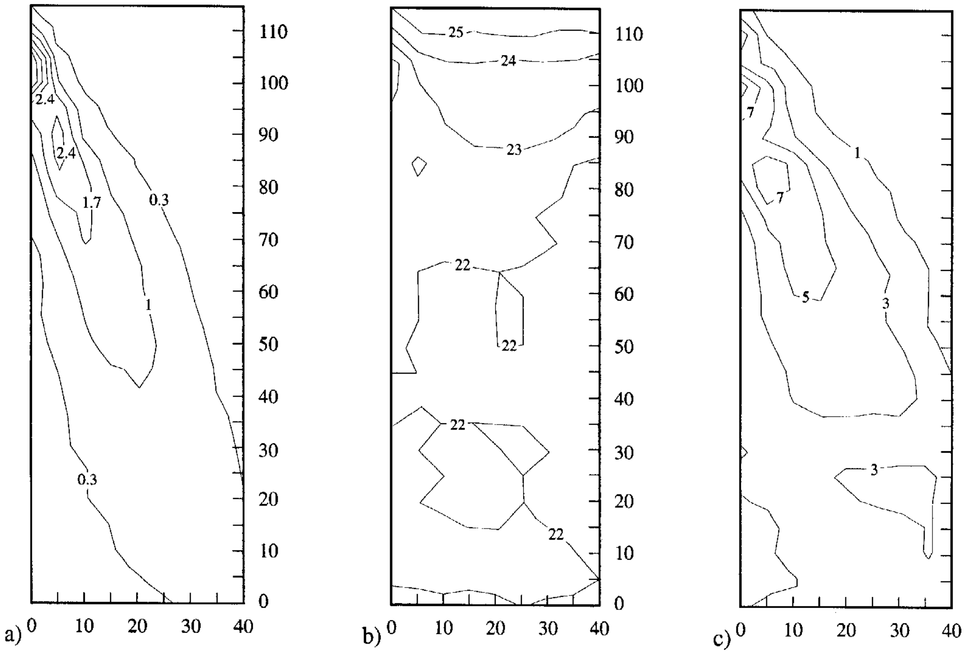

Figure 18. Vertical plane (LSVP 9 × 24) WDS case
a) Velocity, b) temperature, and c) turbulence intensity isolines

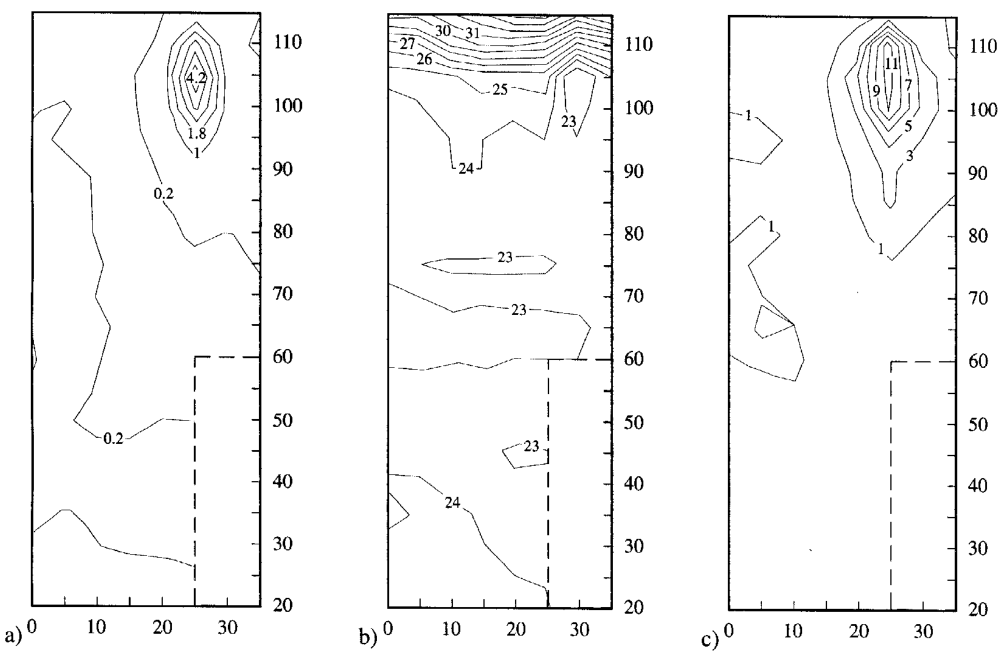

Figure 19. Vertical plane (RFVP 8 × 20) WDF case
a) Velocity, b) temperature, and c) turbulence intensity isolines

- A slight thermal stratification phenomenon occurred in all situations studied, with higher temperatures in the higher planes. Nevertheless, a peculiar behavior was found in the WDF plane with respect to temperature distribution, with very high temperatures (25°C to 34°C) on the top of the plane. The reason for that was probably a hot up-streaming jet formed in the space between the window glass and the solar protection curtain that escaped from the upper part of the window and crossed the measuring plane.
- The turbulence intensity isolines did not seem to be strongly affected by the passenger presence or by the position of the curtains, the patterns obtained for the same planes in different situations being similar.

In Table 2 mean values are presented for PPD and PMV, calculated for planes CUS, CDS, WUS, and WDS. As is apparent, thermal comfort conditions were reached only in the CDS plane. In the other three planes conditions were uncomfortable: two of them indicated by positive PMV values (warm ambient) and one by negative PMV values (cold ambient). The CUS plane was the most uncomfortable. This CUS plane comprised space over the window seat, when the passenger was seated in the aisle seat and the curtains were up.

Table 2. Mean Values of PPD and PMV

Plane	PMV	PPD(%)
CDS	−0.43	8.9
WDS	−1.14	32.5
CUS	2.89	97.9
WUS	1.42	46.7

CONCLUSIONS

The flow field in the passenger compartment of a bus was studied, for a typical summer situation in a temperate climate. A laboratory sectional module was used, both with and without the presence of a thermal mannequin that was used to simulate a seated person inside the bus. Different situations and measuring planes were considered.

The measured values of velocity and air temperature in most of the space corresponding to the occupied zone by a seated passenger were found to be within the ranges prescribed by thermal comfort standards for summer conditions. Nevertheless, comfort conditions were only reached in one situation, if the evaluation criteria are the PMV and PPD indices.

In the situations corresponding to the solar protection curtains up, the very high radiant temperatures implied positive values of PMV, above comfort levels This resulted in high percentages of dissatisfied people (46.7% from the plane close to the aisle and 97% from the window side plane).

For the situations in which the curtains were down, in both cases PMV negative values were registered, but with lower absolute values for the plane over the window seat (CDS plane, where the passenger was seated in the aisle seat), than for the other plane (WDS). For the CDS plane, the indices values were in the comfort range (PPD < 10%); while, for the other plane the conditions beyond comfort levels being on the negative side of PMV, corresponding to a cold sensation.

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