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A numerical study of the air movement and temperatures in large atria and sunspaces

A.D. Lemaire
TNO Institute of Applied Physics (TNO/TPD)
Delft, The Netherlands

A NUMERICAL STUDY OF THE AIR MOVEMENT AND TEMPERATURES IN LARGE ATRIA AND SUNSPACES

A.D. Lemaire
TNO Institute of Applied Physics (TNO/TPD)
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SUMMARY

The air movements and temperatures in two atria and two sunspaces under winter conditions have been simulated numerically. Aim of the study was the prediction of the thermal comfort in the occupied zone of large glazed spaces with different heights and with different types of heating systems. The spaces were rectangular shaped with a base of 24 by 24 meter and a height of respectively 32 and 64 meter.

The three-dimensional, turbulent airflows have been simulated by the computer code WISH3D (a TNO development), using the k-ε turbulence model and the finite volume method. Transient calculations were applied to attain steady state solutions and to detect unstable flows. To prevent expensive computer costs only a limited number of cases has been studied with a reduced accuracy. Nevertheless, useful information regarding the air movements and temperatures in large glazed spaces was obtained from the results.

INTRODUCTION

A general study was made of the disciplines related to the design of large glazed spaces. Part of the study implied the prediction of the movements and temperatures of the air in those spaces. Especially the existence of cold draughts near the floor in a winter situation had to be studied. For this purpose TNO/TPD had to compute the airflow patterns in two types of glazed spaces with different heigths and different heating systems. General design information had to be gathered at reasonable costs.

Based on these conditions, a limited number of eigth cases was chosen and computations with a reduced accuracy had to be excepted. A two-dimensional, cost reducing approach seemed inappropriate because of the expected three-dimensional airflow patterns. First the influence of the height of the space was studied for passive (unconditioned) systems. After that the effects of various heating systems in low glazed spaces were analyzed.

In our case flow simulation has been used as an 'engineering tool' and we will focuss in this paper on the practical aspects of the study.

CONFIGURATIONS AND BOUNDARY CONDITIONS

Configurations

Eight cases determined by eight different configurations were studied. A survey of the cases is shown in table 1. An explanation follows.

Table 1. The studied cases/configurations

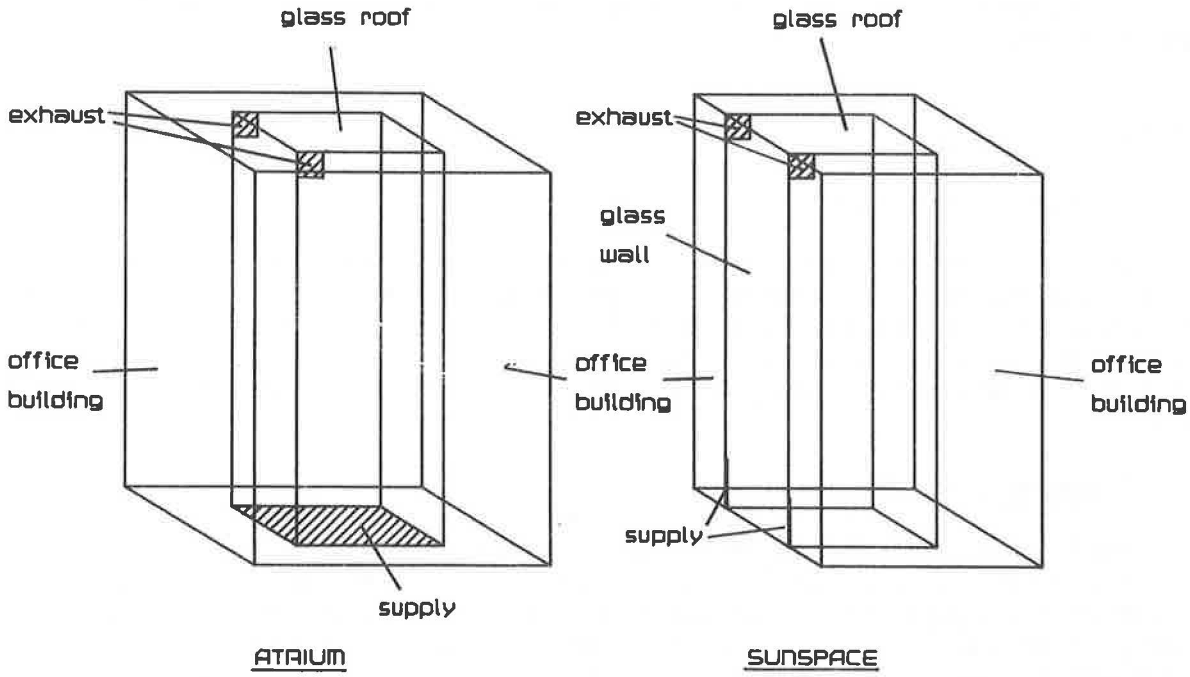
Case	Space	Heating system
1	low atrium	passive
2	high atrium	passive
3	low sunspace	passive
4	high sunspace	passive
5	low atrium	a uniform supply of warm air through the floor
6	low sunspace	a horizontal supply of warm air at the floor near the glass wall
7	low sunspace	convectors on the floor near the glass wall
8	low sunspace	convectors uniformly distributed along the glass wall

Geometry of atria and sunspaces

All glazed spaces are rectangular shaped with a base of 24 x 24 meter. The 'low' and 'high' spaces are respectively 32 m and 64 m high. The types of spaces are an atrium and a sunspace. (See fig. 1) The atrium is sided by a floor, a glass roof and four identical office facades. The sunspace differs from the atrium by the fact that one of the office facades is replaced by a vertical glass wall. There are no obstacles inside the glazed spaces.

The location of the supply and exhaust openings in case 5 and 6 are shown in fig 1. Each exhaust opening is 2.0 m high and 1.87 m wide. In case 5, the whole area of the floor is used as supply opening. In case 6, each supply opening is 4.0 m high and 0.125 m wide.

Fig. 1. Geometry of atrium and sunspace



Convectors are modelled by convective heat sources with the same width as the space. In case 7 only one heat source with a heigth of 0.73 m and a depth of 0.33 is placed on the floor and against the glass wall. In case 8 ten heat sources with a heigth of approximately 1.0 m and a depth of 0.13 m are uniformly distributed along the glass wall.

Surface temperatures

The thermal boundary conditions of each case have been derived from the results of a dynamical simulation with the finite element program BFEP using a zone model with five stacked zones. Estimated convective heat transfer coefficients were used and radiation heat transfer was included. The surface temperatures in the early morning after a cold winter night (ambient -10°C), were chosen as boundary condition for the flow simulation. The temperature in the adjacent offices was 21°C. As a result of the calculation method the floor and the roof have a uniform temperature and each vertical wall consists of five equally sized parts with a uniform temperature. The temperatures are shown in the figures with the results.

All office facades of an atrium or a sunspace have the same surface temperatures. Thus, in case 1 and 2 the two vertical midplanes of the atrium are symmetry planes. In the other cases only one vertical midplane can be treated as a symmetry plane. The remaining boundary conditions are chosen in a way such as not to violate this symmetry.

Heating and ventilation conditions

In case 5 and 6, the space is ventilated with warm air of respectively 23.7°C and 34.0°C. The air exchange rate is 1.0 1/hr, resulting in an exhaust velocity of 0.67 m/s. The supply velocity is 0.0087 m/s in case 5 and 5.0 m/s in case 6. In both cases the values of k and ε in the supply opening are respectively 0.126 m^2/s^2 and 1.96 m^2/s^3

The total strength of the convective heat source in case 7 and 8 is 133 kW. In case 8 the same strength is equally distributed among the ten heat sources.

SIMULATION METHOD

Transport equations

The time-averaged equations of conservation of mass, momentum and energy are solved with the computer code WISH3D. Air is considered an ideal gas and an incompressible fluid and the Boussinesq approximation is used to account for density variations. The turbulence is modelled with the well known k-ε model, using logarithmic wall functions of Launder (1) near the wall.

Computer program

TNO/TPD is developping WISH3D as an alternative to 'industry standard' computer codes PHOENIX and FLUENT. The program is based on a general-purpose computer program for the simulation of turbulent flow, heat transfer and transport of mass species. At present the program has reached a stage where engineering calculations can be carried out for a limited set of problems.

Meanwhile, the development is continuing as new features are added. Some of the main features of the program as it stands today are:

- based on finite volume method with pressure relaxation as e.g described by Patankar (2)
- two- or three dimensional geometry
- cartesian coordinate system, meaning that geometries must either be rectangular or can be so reduced by blocking rectangular subregions
- flexible definition of blocked regions and boundary conditions
- steady or transient treatment
- laminar or turbulent (k-ε model) flow
- convection/diffusion of heat and seperate mass species
- 3-dimensional color graphics output based on GKS
- flexible open program architecture, making the addition of new features fast and easy
- UNIX environment
- optimized for vector computers.

The numerical grid

In all cases a vertical symmetry plane is introduced to reduce the number of grid nodes. To prevent expensive computer costs a rather coarse numerical grid had to be used, resulting in a non-linear grid of 8352 cells for the low spaces and 10656 cells for the high spaces. Figure 2 shows the numerical grid.

The same distribution function is used as in a previous study of a ventilated atrium by Lemaire (3). The distance of the first grid node to the nearest wall is always 0.05 m. Because of this distance errors up to 40% in the convective heat transfer coefficients were to be expected, according to Henkes e.a (4). Comparison of the computed mean convective heat transfer coefficients with theoretical values for turbulent boundary layers showed differences of 20%. In this case a smaller distance could have produced higher errors. Use of a low Reynolds model with consequently a larger number of grid nodes was beyond the scope of this study.

Computation method

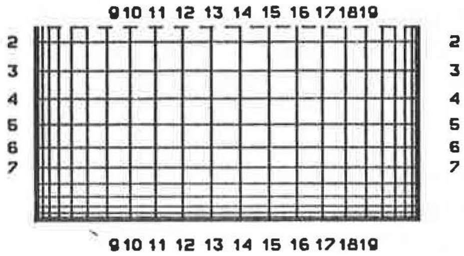
Transient calculations are applied to attain converged steady-state solutions and to detect unstable flows. The main computations are performed on a minisupercomputer (Alliant FX40). Pre- and postprocessing are done on a workstation (SUN 3/50) connected with the minisuper by an ethernet link. The Euler explicit method is used, though a small time step of approximately 0.2 s is needed to meet the stability criterium. A typical case with 8352 volume cells and 9000 explicit time steps of 0.2 s costs approximately 18 hrs CPU time. In case 6, a steady-state computation with the false time step method is performed, because of the very small explicit time steps that would be needed.

RESULTS AND DISCUSSION

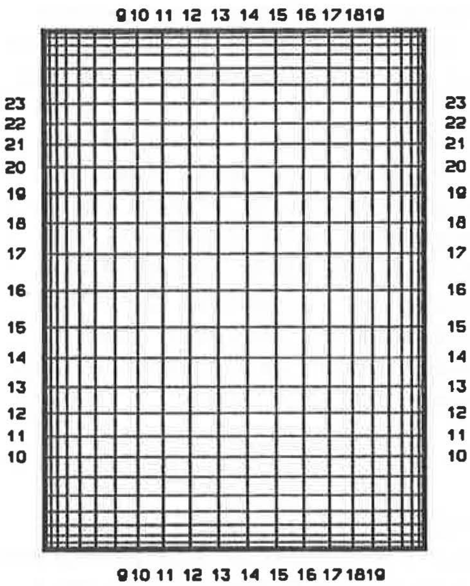
Presentation of results

Velocities and isotherms in two vertical planes perpendicular to the glass wall are presented. The velocities are projected on the plane and

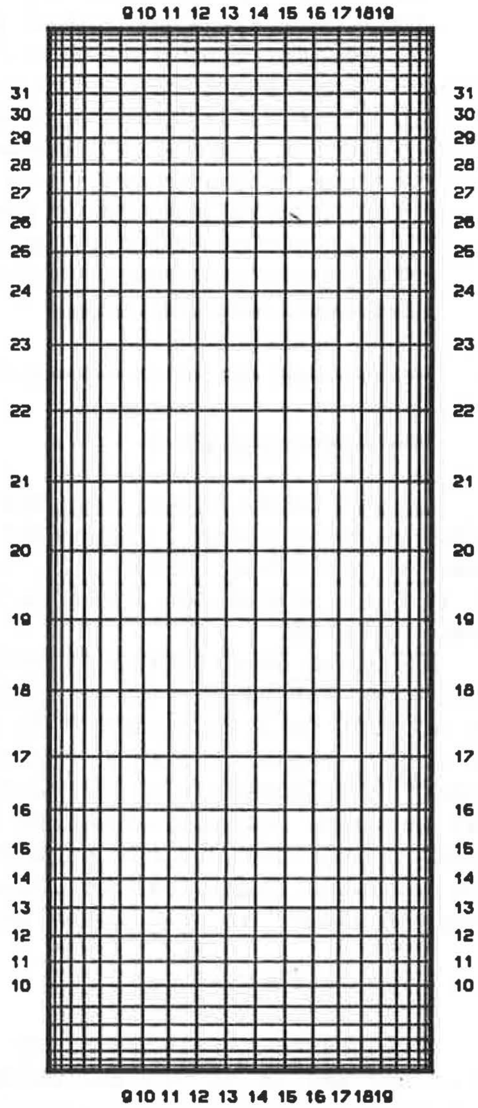
Fig. 2. Numerical grid for low and high spaces



Horizontal plane



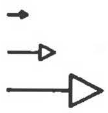
Low space: vertical plane



High space: vertical plane

Fig. 3. Relation between vector length and projected velocity

velocity m/s



0.20
0.50
1.00

represented by vectors. The relation between vector length and projected velocity is shown in figure 3. One vertical plane is a midplane and the other vertical plane is situated at a distance of 4.45 m from that midplane (and 7.55 m from the office facade).

Figures 4 through 11 show the velocity and temperature fields of all cases. As can be seen from the cases with a 'low' space the air movements are typically 3-dimensional.

Air movements and temperatures in passive atria

The flow pattern in the passive 'low' atrium is characterized by a rising air current along the office facades and a column of cold falling air in the middle of the space. (Case 1, fig. 4). Near the floor (in the occupied zone) the velocity of the falling air is approximately 0.6 m/s. The air temperature at this position is at the most 0.5°C lower than the mean air temperature of 5.9°C. The horizontal velocity is approximately 0.50 m/s very near the floor and approximately 0.30 m/s at a heigth of 1.50 m.

The flow pattern in the upper part of the passive 'high' atrium is quite similar to the flowpattern in the 'low' atrium. (Case 2, fig. 5). The velocity of the cold faling air is at the most 0.75 meter in the upper part. This velocity is being decreased in the lower part by the warm surrounding air to a value of 0.05 m/s near the floor.
atrium with respect to the falling air near the floor seems reasonable.

Interpolation between the results of the 'low' and of the 'high' atrium with respect to the falling air near the floor seems reasonable.

Air movements and temperatures in a heated atrium

The heated, 'low' atrium is kept at a temperature of 17.3°C by a uniform supply of warm air through the floor. (Case 5, fig. 6). The flow pattern is characterized by a main vortex resulting in a rising air current along the office facade next to the exhaust openings, and a falling air current along the two facades with the exhaust openings. The velocity in the occupied zone is 0.7 - 0.8 m/s and the temperature is 0.5 - 1.0°C lower than the mean temperature. The main vortex is caused by the asymmetrical exhaust of the air. The positioning of the supply and exhaust openings seems of great importance for the flow patterns. An asymmetrical positioning may cause high air velocities.

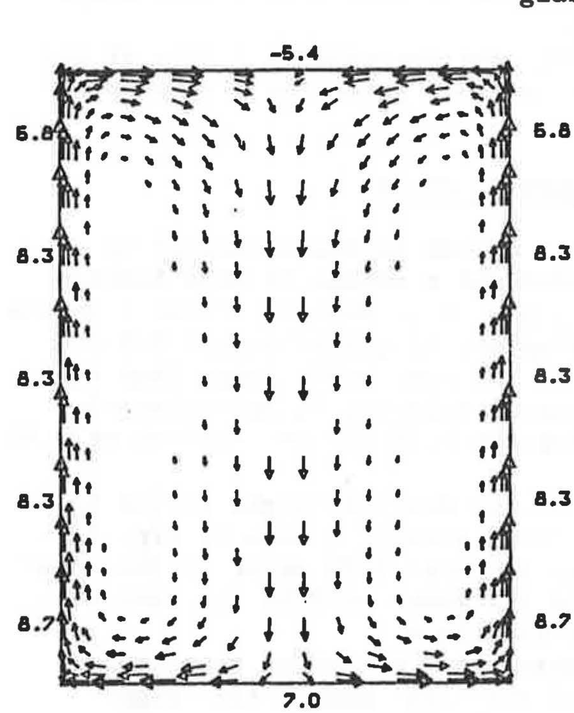
Air movements and temperatures in passive sunspaces

The airflow pattern in the passive sunspaces is characterized by the cold fall along the vertical glass wall and the rising air currents along the office facades.

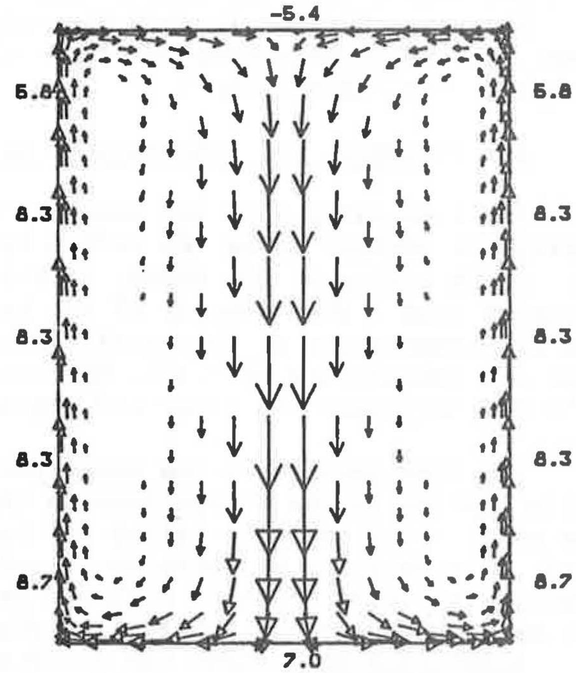
The cold fall in the 'low' sunspace has a maximum velocity of 0.90 m/s. (Case 3, fig. 7). Near the floor the cold fall is bent towards a horizontal flow with a maximum velocity of 0.6 m/s at a heigth of 0.05 m and 0.20 m/s at a heigth of 1.5 m. At this level the air is 0.5 - 1.0°C colder than the mean air temperature of -0.3°C.

The flow pattern in the 'high' sunspace is characterized by a kind of neutral zone in the middle part of the space, where small velocities exist (except near the walls) (Case 4, fig. 8). Above and below this zone the air movements correspond with the flow patterns in the upper and lower part

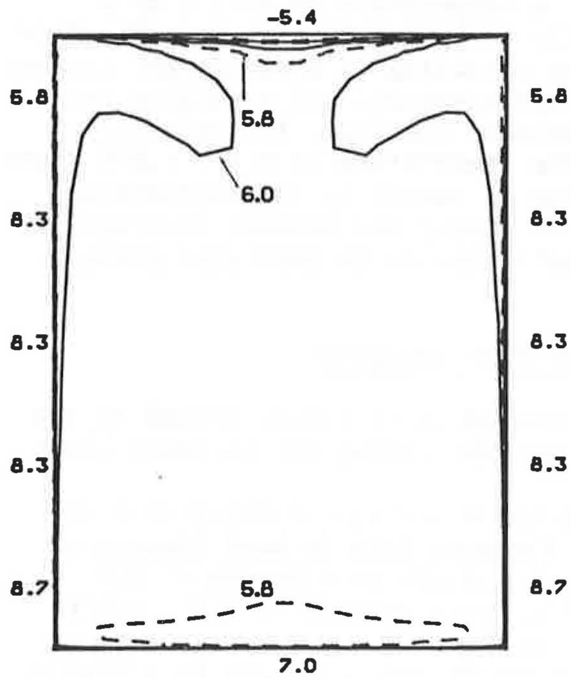
Fig. 4. Case 1, low passive atrium : projected velocities and isotherms



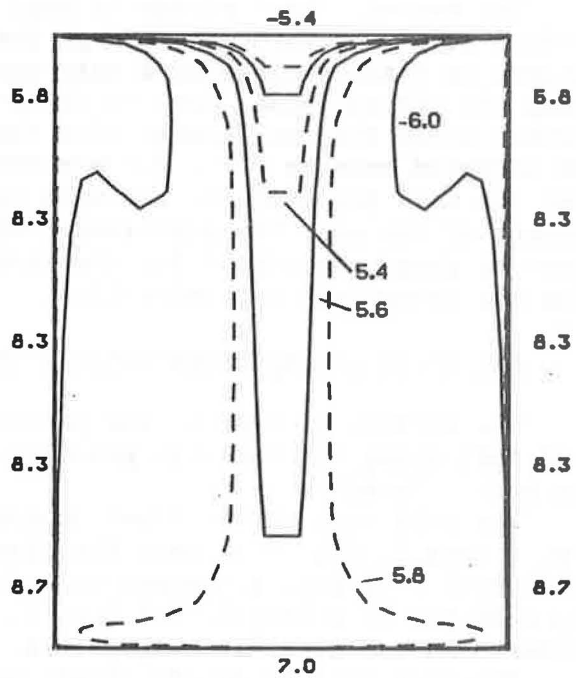
Vertical plane at 4.45 m
from vertical midplane



Vertical midplane

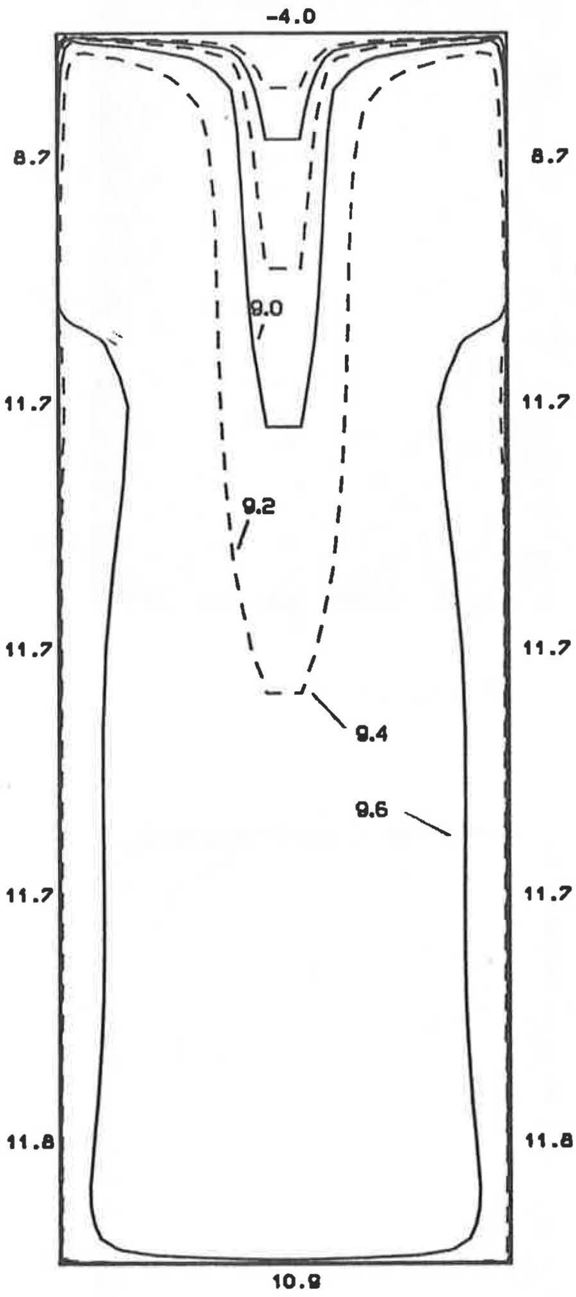


Vertical plane at 4.45 m
from vertical midplane

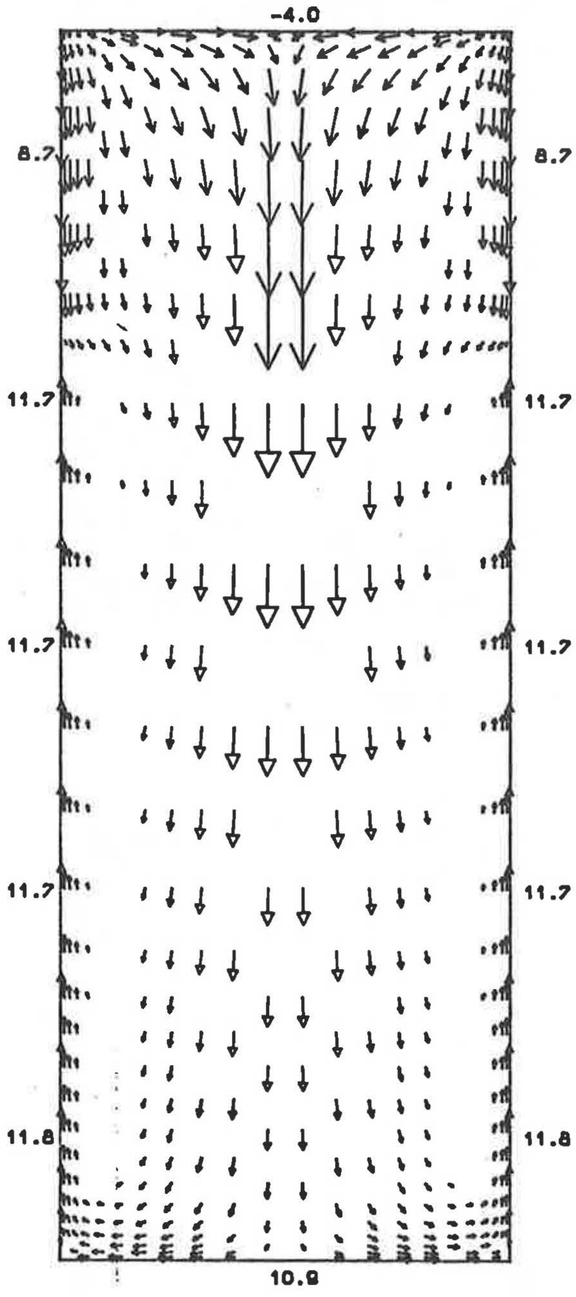


Vertical midplane

Fig. 5. Case 2, high passive atrium : projected velocities and isotherms

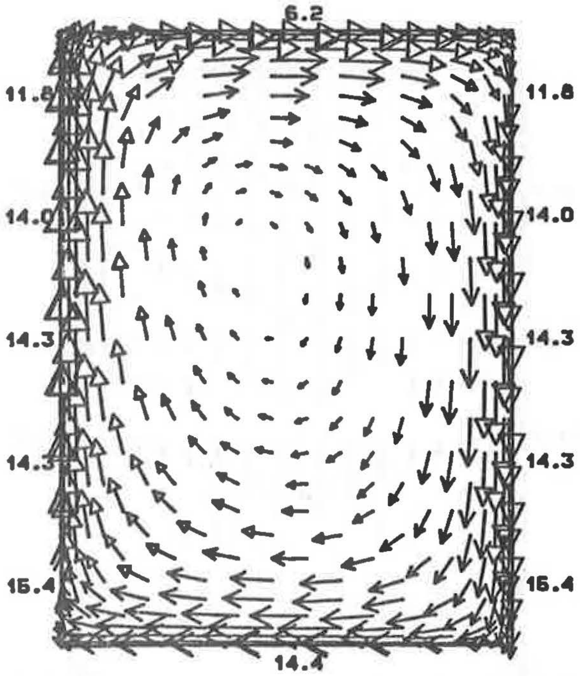


Vertical midplane

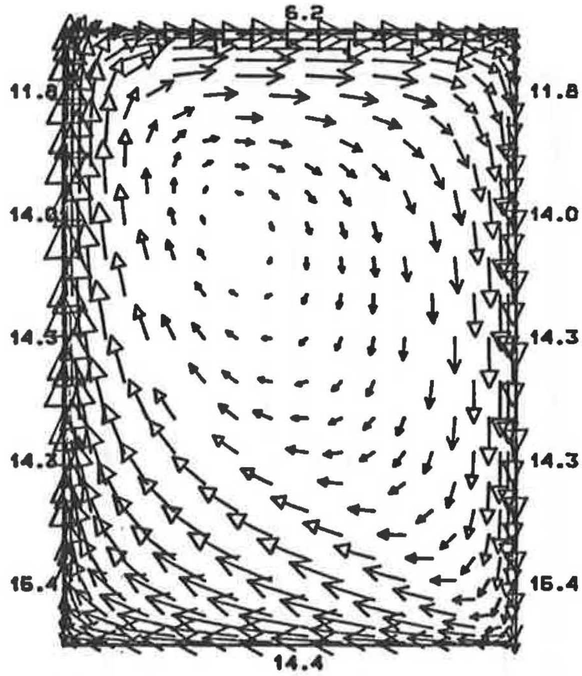


Vertical midplane

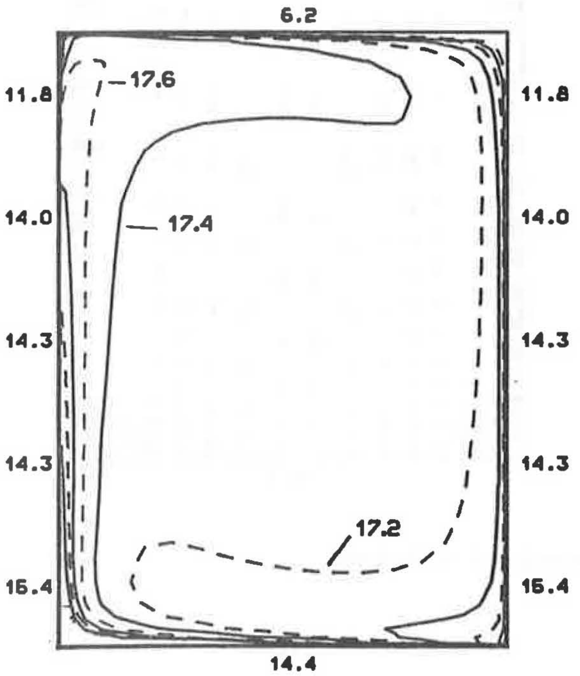
Fig. 6. Case 5, low atrium with a uniform supply of warm air through the floor : projected velocities and isotherms



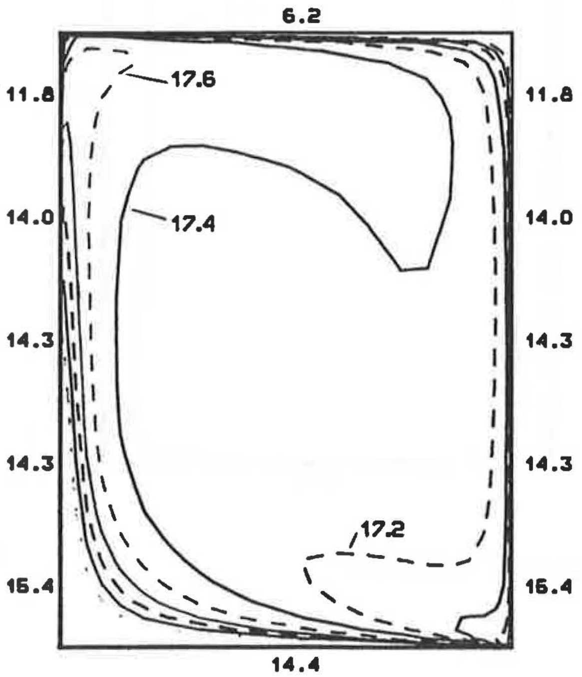
Vertical plane at 4.45 m from vertical midplane



Vertical midplane



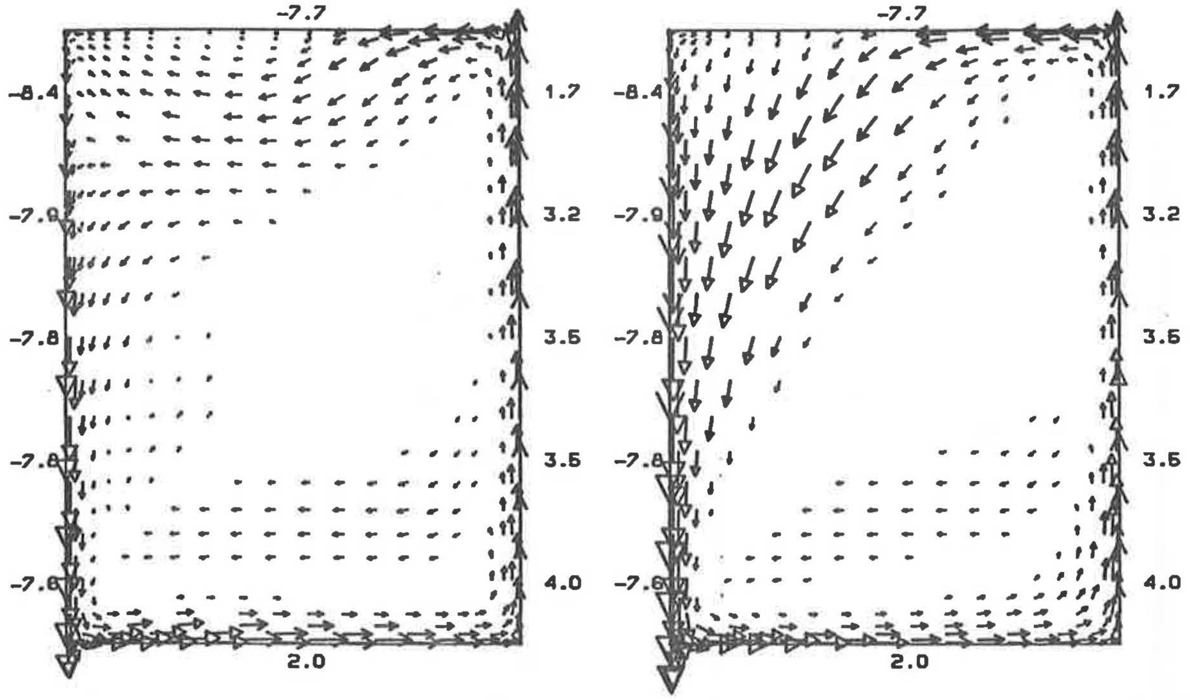
Vertical plane at 4.45 m from vertical midplane



Vertical midplane

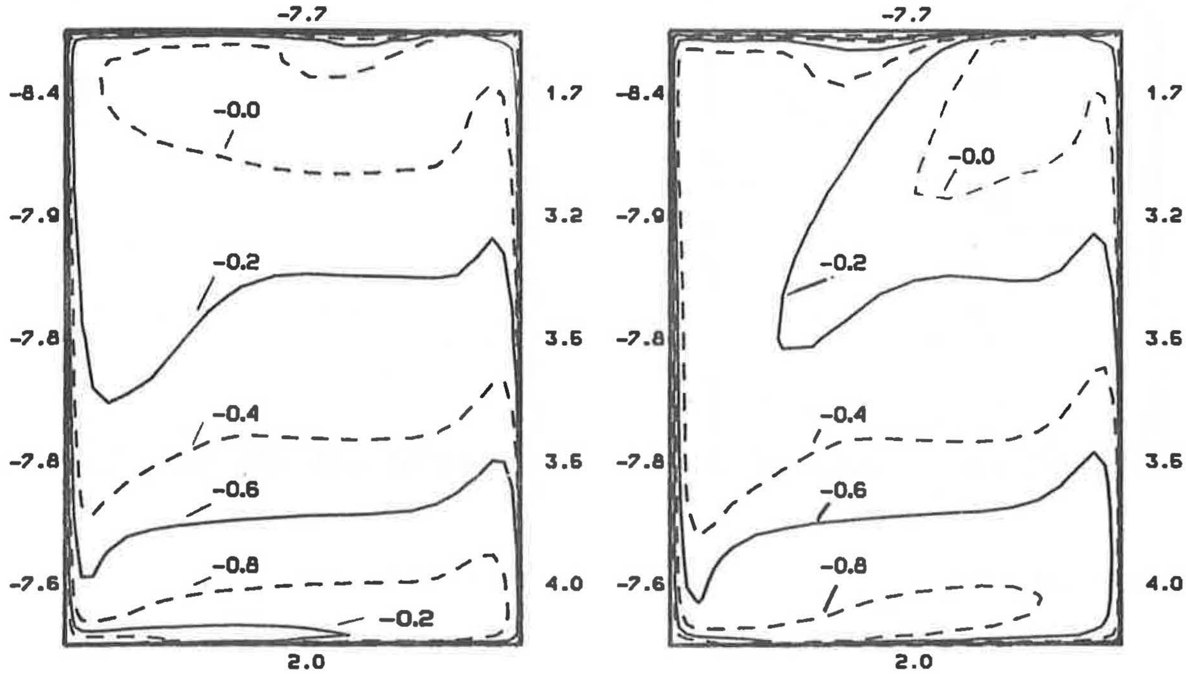
Fig. 7. Case 3, low passive sunspace : projected velocities and isotherms

glass roof



Vertical plane at 4.45 m from vertical midplane

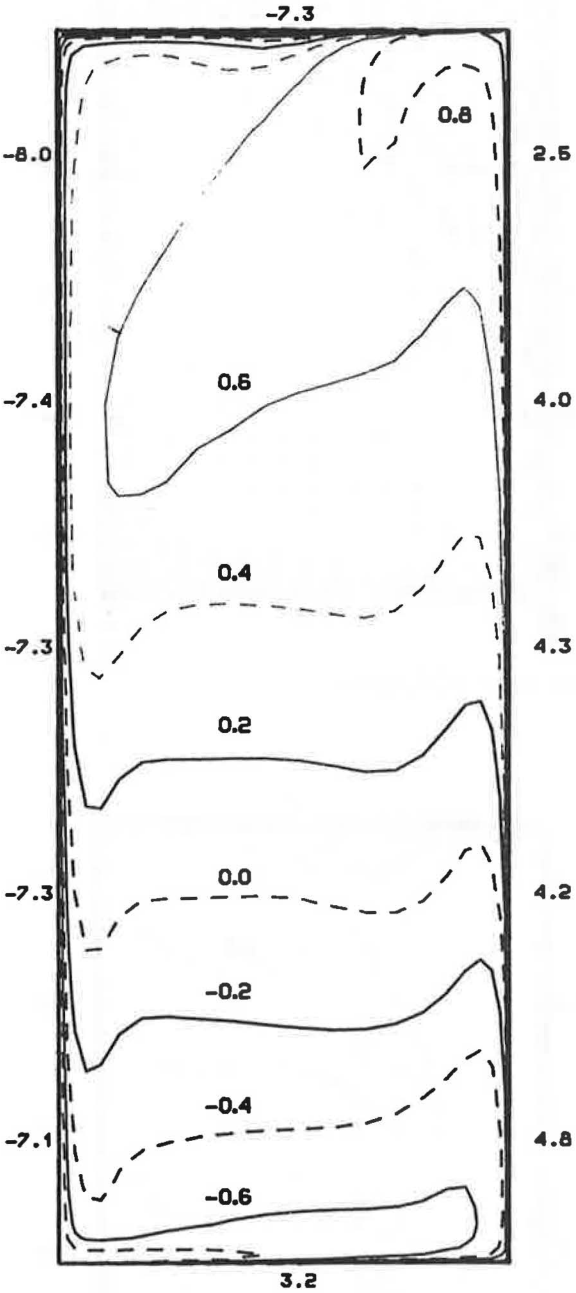
Vertical midplane



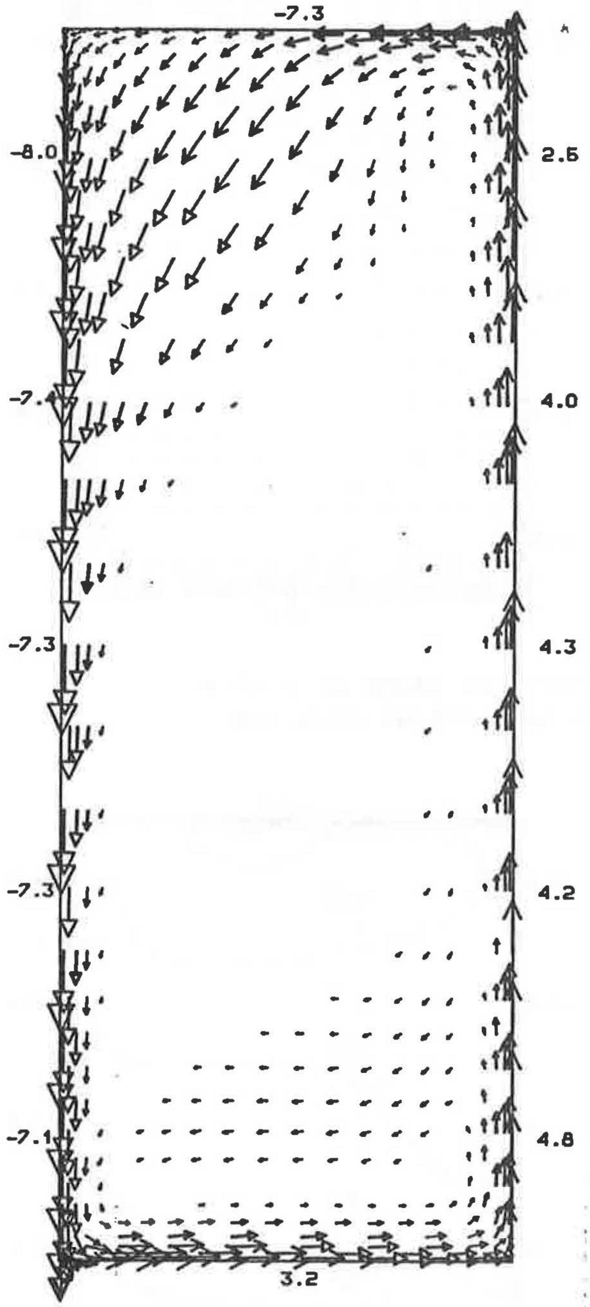
Vertical plane at 4.45 m from vertical midplane

Vertical midplane

Fig. 8. Case 4, high passive sunspace: projected velocities and isotherms



Vertical midplane



Vertical midplane

of the 'low' sunspace. The maximum velocity of the cold fall is 0.95 m/s

Air movements and temperatures in heated sunspaces

Near the floor of the 'low' sunspace the air movements are hardly reduced by the supply of warm air, but the air temperature is relatively higher. (Case 6, fig. 9).The small influence can be explained by the fact that there is no upwardly directed momentum of air along the glass wall to cancel the momentum of the cold falling air.

Heating of the 'low' sunspace by one convector placed on the floor and against the glass wall causes a relatively strong rising air layer along the glass wall. (Case 7, fig. 10). The rising air collides with the cold falling air. This results in an unstable flow pattern with an oscillating collision point. Fig. 9 shows a typical solution. A reversed vortex exists with high velocities of approximately 0.45 m/s near the floor.

Uniform distribution of an equal amount of heat along the cold glass wall seems to be the solution. (Case 8, fig. 11). The reversed vortex still exists, but the velocities near the floor are lowered to approximately 0.20 m/s. The mean air temperature increases from 10.4°C to 11.9°C.

CONCLUSIONS

The air movements in the studied atria and sunspaces are typically 3-dimensional, so a 2-dimensional approach is not allowed.

A reasonable prediction of the airflow patterns in unconditioned spaces can be made at the design stage. Different heigths can be accounted for by interpolation.

Heating by convectors uniformly distributed along the glass wall seems to be the best way to prevent draugth near the floor in case of sunspaces.

Grid refinement is needed to avoid inaccurate results caused by numerical diffusion and inaccurate convective heat transfer computations.

In general, the numerical study of airflow patterns in large glazed spaces seems possible at reasonable costs. Useful information regarding the air movements, temperatures and thermal comfort can be deducted. A comparison with measured data is still needed.

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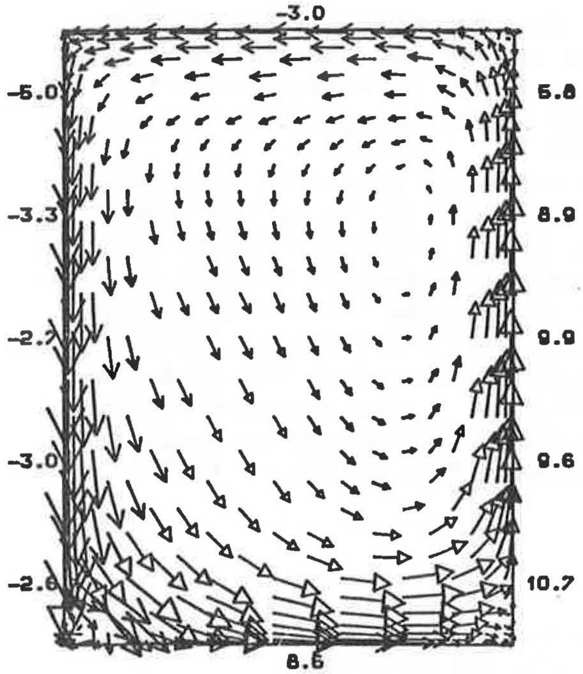
(1) Launder, B.E., and Spalding, D.B., The numerical Computation of Turbuent Flows, Computer methods in Applied Mechanics and Energy, 1974, 269-289.

(2) Patankar, S.V., Numerical Heat Transfer and Fluid Flow, Mc Graw-Hill, New York, 1980

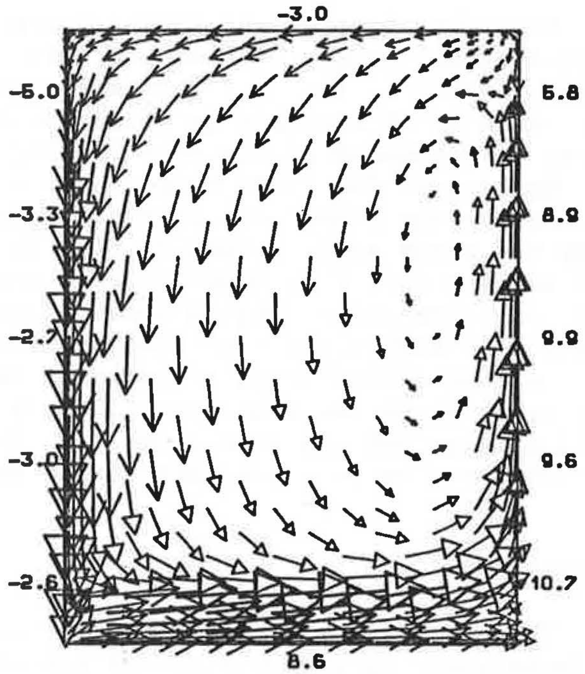
(3) Lemaire, A.D., The numerical simulation of the air movement and heat transfer in a heated room resp. a ventilated atrium, Roomvent 87 conference, Stockholm, 1987

(4) Henkes, R.A.W.M., and Hoogendoorn, C.J., Comparison of turbulence models for the natural convection boundary layer along a heated vertical plate, Int. J. Heat Mass Transfer, 1989, 157-169

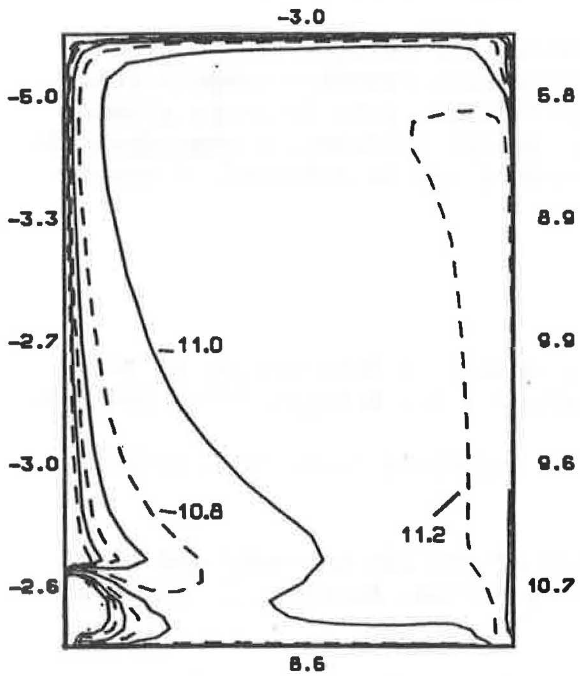
Fig. 9. Case 6, low sunspace with a horizontal supply of warm air at the floor near the glass wall : projected velocities and isotherms



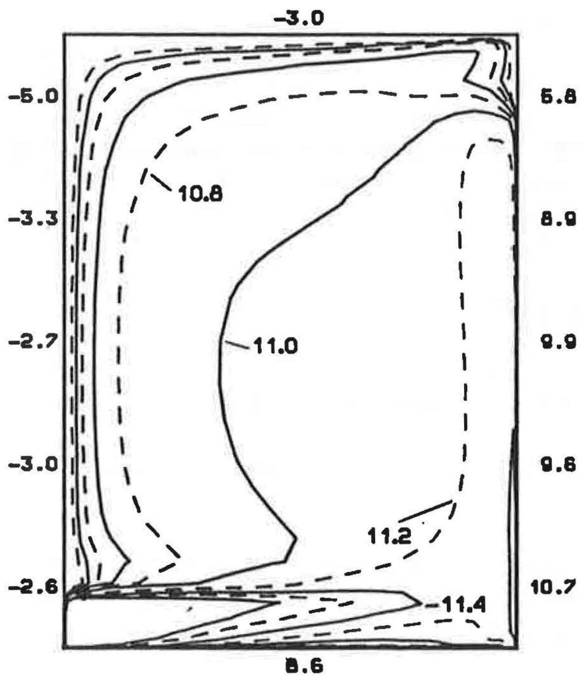
Vertical plane at 4.45 m
from vertical midplane



Vertical midplane

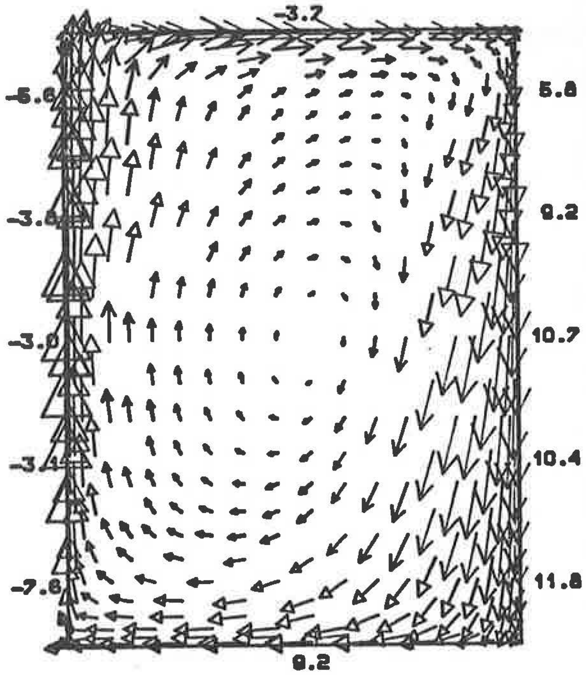


Vertical plane at 4.45 m
from vertical midplane

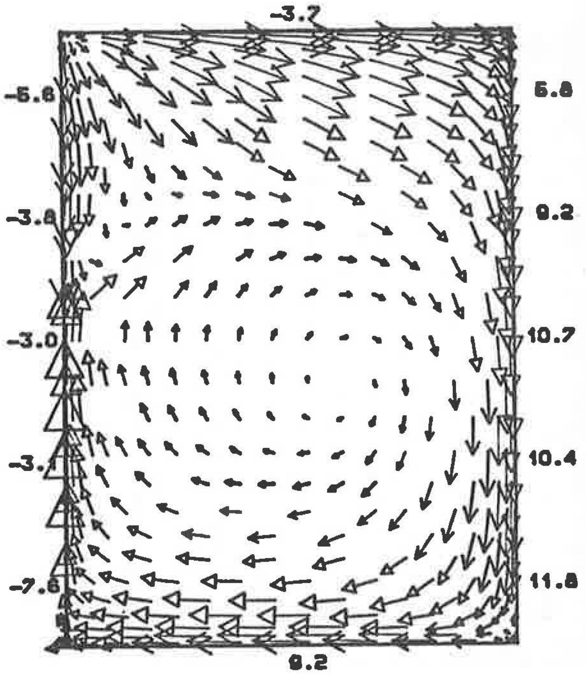


Vertical midplane

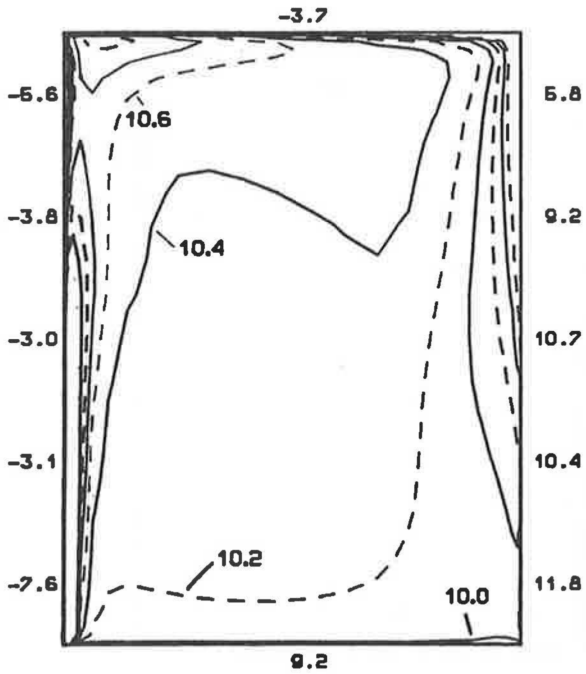
Fig. 10. Case 7, low sunspace with convectors on the floor near the glass wall : projected velocities and isotherms



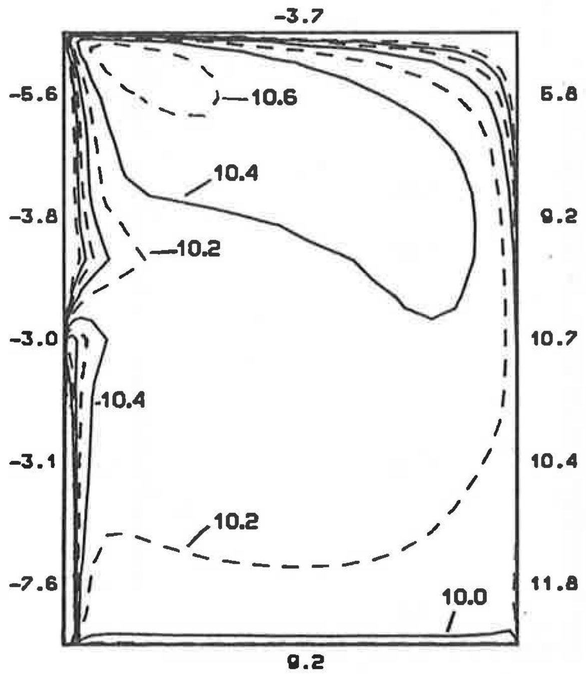
Vertical plane at 4.45 m from vertical midplane



Vertical midplane

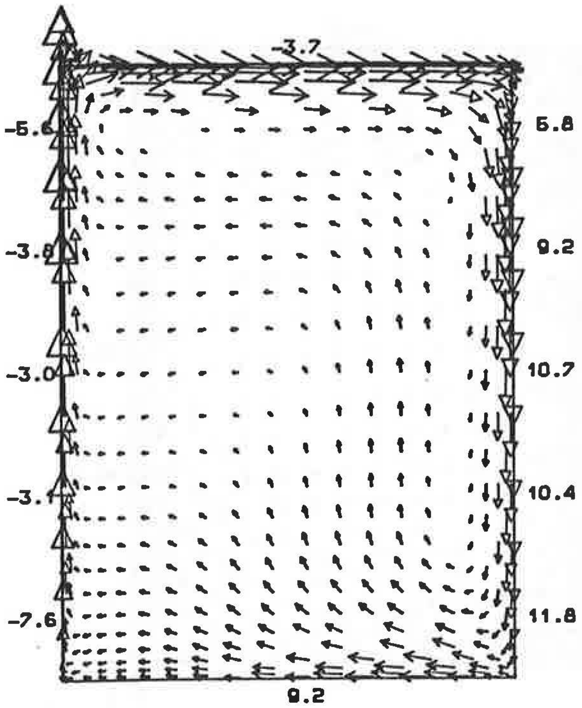


Vertical plane at 4.45 m from vertical midplane

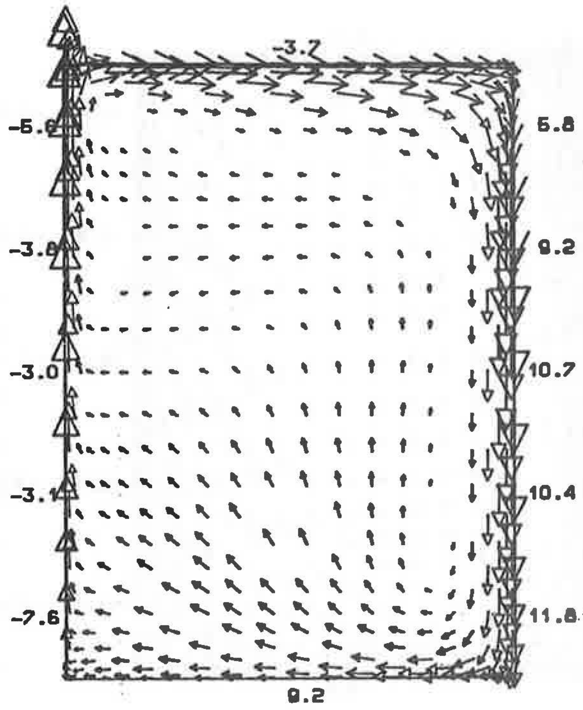


Vertical midplane

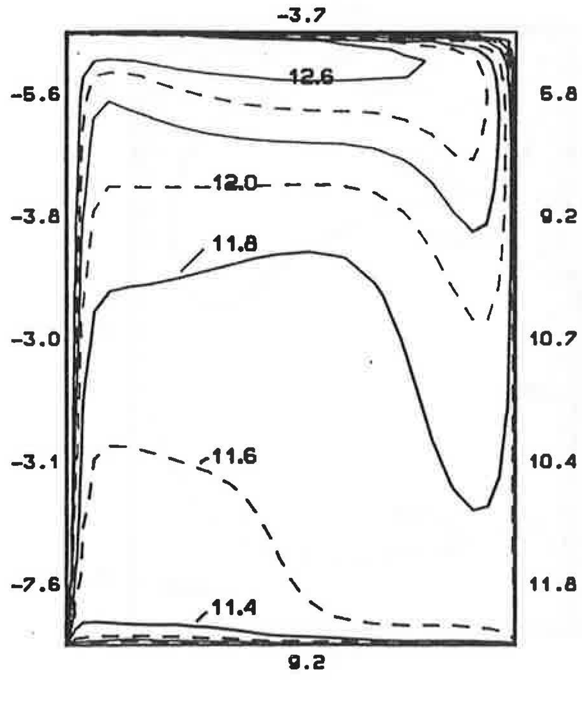
Fig. 11. Case 8, low sunspace with convectors uniformly distributed along the glass wall : projected velocities and isotherms



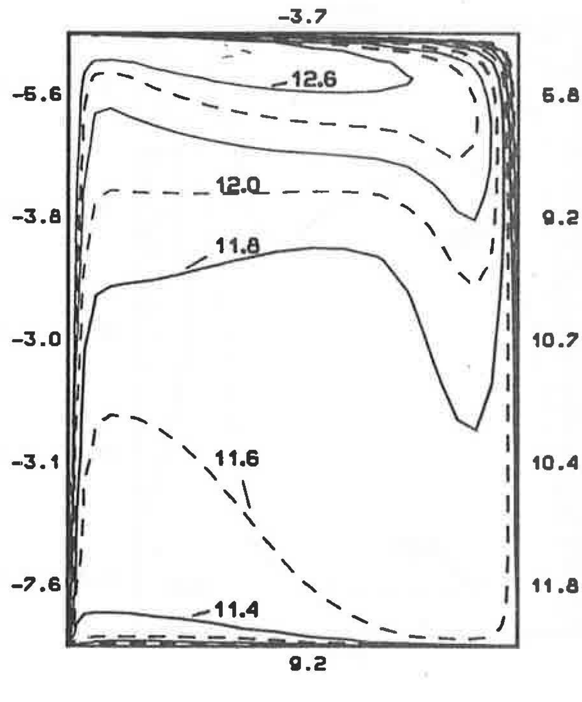
Vertical plane at 4.45 m
from vertical midplane



Vertical midplane



Vertical plane at 4.45 m
from vertical midplane



Vertical midplane