AIR FLOW PATTERN AND TEMPERATURE FIELD SIMULATION IN A LARGE GLAZED SPACE

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ABSTRACT

Air velocity and air temperature are, in large glazed spaces, very heterogeneous and time dependant. Indoor and outdoor thermal conditions, localized solar radiation effects and ventilation systems are the conditions for mixed convection situations which produce, in large enclosures, significant velocity and temperature gradients.

In this paper we describe the numerical techniques and processes that enable us to take hese three types of conditions into account.

By investigating the specific geometry of a covered street and the thermal and sun conditions of an average sunny winter day in Nantes, we show how different inlet and outlet situations and minor geometrical adjustments modify the temperature field and flow pattern.

Variations of temperature fields are significant. It would seem, therefore, that such a simultaneous numerical analysis of the effects of these three types of physical parameters might constitute, after further developments, a starting point from which to provide powerful and useful tools for the design of large glazed spaces.

INTRODUCTION

The revival of interest in galleries, atriums or conservatories can be explained, in addition to their symbolic aspects, by their amenity value and the energy savings they are expected to provide. To obtain those potential savings, an accurate prediction of the indoor air flow pattern and temperature fields is necessary. That must be done according to present day standards of comfort and with the aim of reducing heat losses in winter and overheating in occupied areas in summer.

The two ambient physical parameters, air velocity and air temperature, are, in large glazed spaces, very heterogeneous and time-dependant, due to three types of conditions ; indoor and outdoor thermal conditions, the ventilation system, and the effects of solar energy.

Our instrumental investigations in the field of thermal and micro-climatic analysis of projects leads us to offer numerical tools in order to examine, in three dimensions, the combined effects of these conditions. The numerical approach to air flow simulation enables interior temperature field and air velocities to be analysed simultaneously and it seems particulary rewarding to use this approach in thermal simulations of high and large glazed spaces because of the possibilities it offers of investigation in 3D.

In our presentation, we are going to describe the investigation procedure employed for the simulation of a covered street. Three codes are used:

- SIMULA software, developed in our laboratory is a multizoning thermal simulation code. It enables us to define realistic thermal conditions and to evaluate dynamically thermal exchanges in spatial configurations.
- SOLENE software, also developed by our laboratory, analyses the geometrical configuration of the building in order to predict, over time, sunny and shaded spaces and to evaluate solar energy on the walls. Present software developments in geometrical form factor calculation enable us to elaborate a realistic solar reflection model.
- N3S fluid dynamic calculation code, produced by the Electricité de France Company is used,with a finite elements method, for simulating 3D turbulent air flow. The results of solar and thermal simulations may be integrated at that level, as boundary conditions, to explore the temperature field and air velocities all over the space.

We emphasize, in this paper, the capability of these numerical simulations to evaluate contrasted ventilation strategies :

- ventilation of the covered street with air entrance in the lower part of the street and extraction at the roof level,
- preheating the bordering buildings change air ; the air of the covered street is extracted at every floor of the bordering buildings,
- increased preheating by concentration of the extraction at the lower part of the covered street,
- strengthening of this last option by minor geometrical adjustments.

INVESTIGATION PROCEDURES

To illustrate our intrumental presentation, we use the simplified geometry of an educational building organized along the two sides of a covered street that contains four floors of classrooms and services. The length of the street is about 100 meters, the width about 13 meters and the height about 15 meters; the roof is glazed. The profile is given in figure 0.e. We take advantage of the great length and symmetry of the building to perform the three dimensional simulations on a transversal section of the street.

The simulation of the flow pattern is performed by N3S that solves the Navier-Stokes and continuity equations. The k-ε model is used to take into account the turbulent effect of the air flow with a high-Reynolds number. The N3S code solves this set of equations using a finite elements discretization method to deal with complex geometry. It therefore requires a meshing of tetrahedra to compute unknown variables in the domain (velocity vector, pressure, temperature or passive effluent concentration). The triangular meshing of the skin on boundaries supports the limit conditions : turbulent boundary conditions and thermal constraints at the wall surfaces [2] and velocity of air in the different inlets which are simulated.

This surfacic meshing of the geometry corresponding to walls and rooves constitutes the geometrical basis on which we operate to interface data obtained from solar and thermal investigations. Figure 0.f shows the meshing on a transversal section of the street. The software developed in our laboratory allows us to evaluate realistic boundary conditions to simulate mixed ventilation by:

- determining the spatial distribution of direct solar energy transmitted by the glazed roof,
- multi-reflecting incident energy using geometrical form factors between triangular facets,
- evaluating the thermal response of elements,
- and, finally, giving for each element, the thermal condition specified by a given temperature or flux.

We will now examine how we establish these thermal boundary conditions in the fluid dynamic code for realistic simulations, in steady-state, of the mixed convection with the aim of analysing the air flow pattern and indoor temperature distribution produced by different ventilation systems.

SOLAR SIMULATION

The SOLENE program performs solar simulations [3]. The geometry of the street is expressed in the form of polygonal facets. In order to adapt to the spatial discretization required to solve the fluid problem, we need to determine insolation conditions on the triangles of the surface meshing of the street, walls, ground and rooves. To do this, we use a technique called the "masking effect" that enables us to determine, for a point located in the space, the insolation periods for that point. The technique is based on the numerical analysis of the image of the surrounding site, viewed from this point, and realized through an appropriate spherical projection. From this perspective (figure 0.d), the projected image of the sun at a particular time of day or year is represented as a point.

Thus, for every moment corresponding to a solar position, we can discover the relative situations of facet images in relation to the sun's ray. Two cases occur :

- the projected point of the sun is inside an opaque facet; the facet inhibits the insolation of the simulated point,
- the projected point of the sun is inside a transparent facet; the simulated point receives transmitted direct solar radiation that can be evaluated.

Therefore to obtain information about the solar energy transmitted through the glazed roof on interior wall facets, we must add information about materials (opacity/transparence and solar coefficients) to the geometrical definition of facets.

In order to investigate any part of the street, we perform the same simulation for each triangle of the meshing, assuming that the center of gravity is the observer. With this technique of projection, we can easily obtain time dependent solar values for a given day.

MULTI-REFLECTION AND FORM-FACTOR

The received solar radiation is not completely absorbed by the walls. Depending on the color of the surface, a part of this direct radiation is reflected towards the immediate surroundings (figure 0.a). Shaded facets may intercept energy through the multi-reflections produced inside the volume of the street.

We make the asumption that the interreflection occurs between ideal diffuse reflectors, that are acceptable as normal building materials. With isotropy conditions, the reflected energy is therefore directly governed by the form-factors between facets. In this case, the form-factor Fij represents the fraction of reflected solar energy leaving surface j and landing on surface i. The reflected flow of a surface i depends only on its solar reflectivity coefficient ρ_i.

After multiple reflections, the remaining reflected energy tends towards zero. The balance of exchanges by reflection may be expressed by means of a set of equations; there are as many equations as there are triangular elements in the meshing. In matrix form, the system can be written :

$$[\delta_{ij} - \rho_i F_{ij}].[B_i] = [\rho_i \Phi_i]$$

where

Bi is the unknown value of the energy reflected by element i

ρi is the reflective coefficient of element i

Φi is the value of incident direct solar energy on element i

Fij is the form-factor between elements i and j.

Solving this equation system gives B values; thus, the effective solar energy absorbed by a wall element j of the mesh is :

$$\alpha_j \Phi_j + \alpha_j \sum B_i . F_{ij}$$

where αj is the solar absorption coefficient of element j.

The form-factor expresses the geometrical relationship between two surfaces. The form-factor computation implies an evaluation of a double integral (figure 0.c) and several techniques have been developed to enable this calculation to be performed [4]. A specific method is proposed by Yamanouti who gives a formula based only on the geometric definition of planar facets in 3D (polygonal contour). For a surface element dA with a normal vector n, the form-factor evaluated in relation to a facet described by its polygonal contour of n edges is (see figure 0.b):

$$F_{dA} = \frac{1}{2\pi}\sum_{i=1}^{n} \cos \alpha_i \, . \, d\beta_i$$

where

α is the angle between the normal vector n and the normal vector to the plane constituted by P representative of dA and the considered edge AB;

β is the angle between edges PA and PB

Nevertheless, the application of this formula requires that the two faces are totally visible one to another. Generally, in complex geometries, there are elements that can inhibit that mutual visibility or the volume may present some concavity. The problem is that, for a view point corresponding to the surface for which we want to establish the form-factors, we have to determine the geometry of visible elements.

A hidden surface process must therefore be integrated with the computation of each form-factor. We do this with the boolean geometrical operations used by SOLENE for the determination in 3D of the sunny parts of facets. The method is the same as that we have seen previously in the solar simulation phase, except that we have now to construct the visible polygonal portions of facets in the plane of the projection. After the application of this geometrical algorithm for removing hidden parts of objects, we apply, to each visible facet, an inverse transformation that replaces polygons in their original coordinate system. It is only after this preliminary operation that we can compute the formula to evaluate the form factor for a given facet.

For surface meshing with a large number of elements and possible obstructions between facets, the computation of the form-factors and the resolution of the set of equations for reflection evaluation requires powerful computers. It would therefore be interesting to work on a meshing of dimensions different from those we need in order to compute air flow. Consequently, a correspondance between solar and air meshing would be necessary.

Solar constraints on walls are not restituted directly. Inertia and the materials of the wall introduce a delayed thermal response. We have to examine the wall under dynamic conditions in order to calculate the resultant heat exchange with the air. For this purpose, we use SIMULA software developed in our laboratory. SIMULA(5) is a multizoning thermal code which can enable us to estimate, for each step and for each kind of element of the boundary meshing, the thermal fluxes caused by the exchanges with the bordering buildings and the solar fluxes. Consequently, we are able to introduce correct boundary conditions, under dynamic conditions, for each element in the CFD code. That is again theoretical. With present day calculator performances, that would require much too much calculation time. So we have simplified these conditions. For the purposes of this research, we used SOLENE and SIMULA for the evaluation of realistic average conditions.

AIR FLOW SIMULATIONS and COMPARATIVE RESULTS

In the first case, symmetrical air inlets and outlets were located respectively in the lower part of the lateral walls and in the vertical part of the glazed roof.

The air flow was controlled at the supply inlets by specifying a uniform and constant velocity of 0.4m/s corresponding to an air change rate of 3.25 volumes/hour and a Dirichlet condition on temperature (temperature assumed to be constant and equal to 7°C). The air outlets were free with no constraint condition.

The boundary conditions at the wall surfaces were

- on the one hand, an impermeability condition, a friction condition on tangential stress and the development of a turbulent layer,
- on the other hand, thermal conditions which were, here, the following flux conditions :
- a constant outdoor temperature of 7°C
- a constant air temperature of 20°C for bordering buildings
- a zero flux from the ground
- a constant flux from the insolated walls of 160 W/m2 (which is the mean value given by SOLENE and SIMULA for a sunny winter day in Nantes, France)

Figures 1.a and 1.b show, respectively, velocity vectors and velocity field in a theoretical situation where thermal effects on the air flow were ignored. The principal air flow occupied the mid axis of the street. Here the mean velocities were about 0.15m/s. Along the lateral walls, the downward flow was characterized by very low velocities. In Figure 1.a, vizualisation of the trajectories of some air particles in the flow clearly shows the air flow in this theoretical configuration.

When the thermal boundary conditions were introduced, the air flow pattern was greatly modified. In our case, these thermal conditions were assymmetrical with a concentration of the solar fluxes on the right hand side of the transversal section of the street. Figure 1.c and 1.d visualize the air flow pattern in that mixed convection situation. The assymmetrical conditions clearly produced a stack effect near the right hand wall where the air velocity reached about 0.6 m/s. Two contrasted recirculation zones appeared. First, in upper levels of the street, air velocities were significant with a mean value of about 0.25 m/s. Secondly, below a level of about 9 m, air velocities were very weak. Figure 1.e represents the temperature field. Again, two zones clearly appear. Below the level of 9m, there was a regular stratification of the temperature with a vertical gradient of 10°C. Above, the mixing of the air was better and caused a large homogeneous zone to appear at the temperature of 18°C.The additional temperature gradient (11°C) was horizontal and located near the hot walls.

In the second case, symmetrical air inlets were located in the vertical part of the glazed roof and symmetrical outlets were located on each floor of the lateral buildings.

The air flow was controlled at the extraction by specifying a uniform and constant velocity of 0.1 m/s corresponding to an air change rate of 3.25 volumes/hour,the same as that of the first case.The air intlets had no constraint condition for velocity and a Dirichlet condition on temperature (temperature assumed to be constant and equal to 7°C).

The boundary conditions at the wall surfaces were the same as those we used in the first case.

Figures 2.a and 2.b show, respectively, Velocity Vectors and Velocity Field in the theoretical situation where thermal effects on the air flow were ignored. As in the first theoretical configuration, the principal air flow occupied the mid axis of the street but here the velocities were lower and the flow was downward. Along the lateral walls velocities were even lower but the mean flow was upward. Consequently, when thermal boundary conditions were introduced, the displacement ventilation effects and the forced ventilation effects were cumulative. Figures 2.c and 2.d show, compared with Figures 1.c and 1.d, an increase in velocities and an extension of the active recirculation zone. All over the street, air velocities were significant.The mixing of air was great and the temperature relatively homogeneous with a great part of the street at an average temperature of about 14°C and a localization of the steep temperature gradients near the sunny wall (Figure 2.e).

This case was, with simplified geometry and in steady state, the simulation of the preheating by the covered street of the air change of bordering buildings. The results which were obtained, if exploited to that purpose, show an acceptable inside temperature for the covered street and heterogeneous conditions for air inlets with air change at 7°C above outdoor temperature on the left hand side of the street and an average gain of 11°C on the right hand side.

The third case strengthened the effects of forced ventilation. The thermal conditions were those of the first and second cases. The air change rate was again 3.25 Volume/hour but the ventilation system was different with symmetrical air inlets located, as in the second case, in the vertical part of the glazed roof and symmetrical outlets concentrated on the ground floor of the lateral buildings. Figures 3.a and 3.b show that, in the situation of forced ventilation alone, high velocities were observed along the mid axis of the street and also, right up to the top of the walls, two lateral zones of recirculation with, in contrast with the first case, an upward flow near the walls. So the results were inverse to those of the first case. It may be observed that the velocities field was not exactly inverse but this was because the applied constraints were not exactly opposite.

When thermal boundary conditions were introduced, these upward flows strengthened, as in the second case, the stack effect near the insolated walls and that situation created a recirculation zone which was very active wih high velocities (Figures 3.a and 3.b).

Consequently, the mixing of air was great.The temperature was increased to about 16°C in a large part of the volume. That is to say 2°C higher than in the second case, a comfortable temperature for a pedestrian using the street and an important gain if the air of the street was used as change air for the bordering buildings.

The fourth case measured the impact of a minor geometrical adjustment on the strengthening of the mixing effect observed in the third test. In the original geometrical configuration the passageway of the fourth floor was obtained by a corbelling out of the concrete floor. This configuration pre-supposed a limitation for the development of the stack effect. For the measurement of this limitation, footbridges served as substitutes for the corbels. The gap between walls and footbridges was 0.3m wide. Differences that we observed in the air flow pattern and air temperature field were not really significant taken as an average. Nevertheless, a modification of the active recirculation could be observed and there was a strengthening of the air velocities above the left passageway (Figure 4.a). Consequently, the mixing of air was improved and produced a more homogeneous temperature in that part of the street (Figure 4.b).

Figure 4.c shows the effluent diffusivity of this configuration and can be compared with the heterogeneous situation of first case (Figure 1.f)

CONCLUSION

The simultaneous numerical analysis of indoor and outdoor thermal conditions, solar radiation effects and ventilation system give, for a large glazed space, contrasted results when the air inlet and outlet situations are modified or when minor geometrical adjustments are made. For comparative simulations, geometrical simplifications and studies in steady state still appear necessary. With further developments and the improvement of calculators however, such a numerical approach to the combined effects of thermal and solar fluxes and the ventilation system could constitute a good basis for elaborating powerful tools for current architectural and engineering practice. These tools would be particularly useful in the design of large glazed spaces such as the covered street we have tested.

The tools already offer an excellent visual means of providing an understanding of mixed convection effects. To that pedagogical end, our laboratory is going to simulate, using this approach, the mixed convection effects in buildings which are architectural references.

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figure 0.a

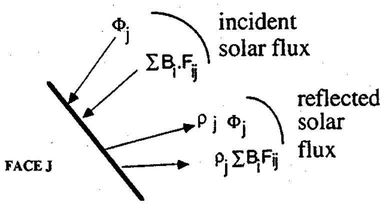
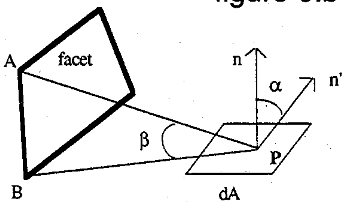
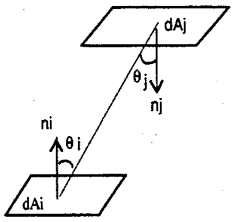


figure 0.b





$$F_{A_iA_j}=\frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{\cos\theta_i\cos\theta_j}{\pi r^2}dA_i dA_j$$

figure 0.c

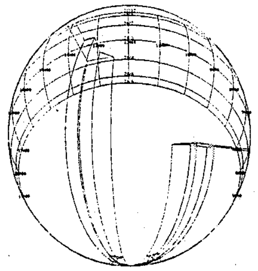


figure 0.d

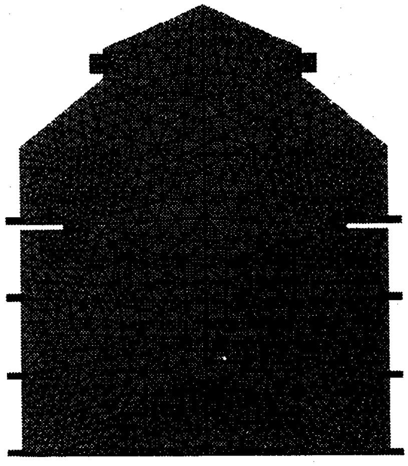


figure 0.f :MESHING of the COVERED STREET

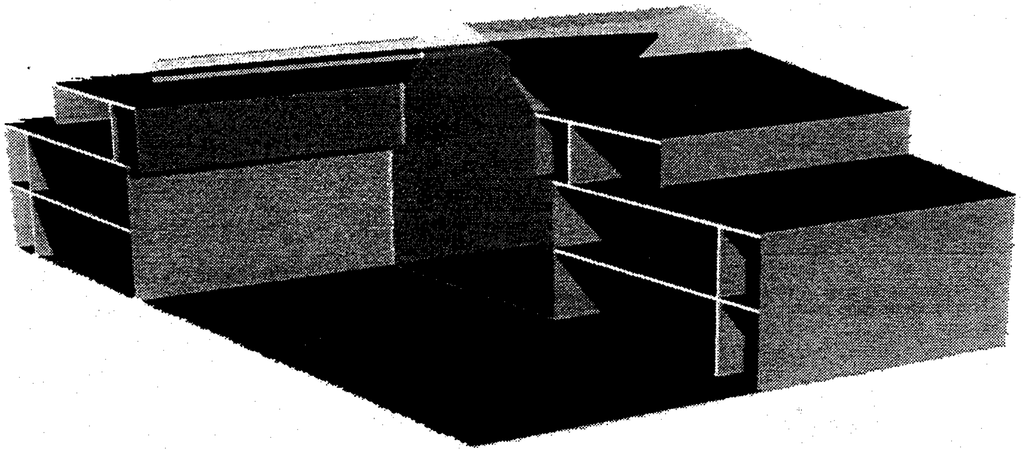
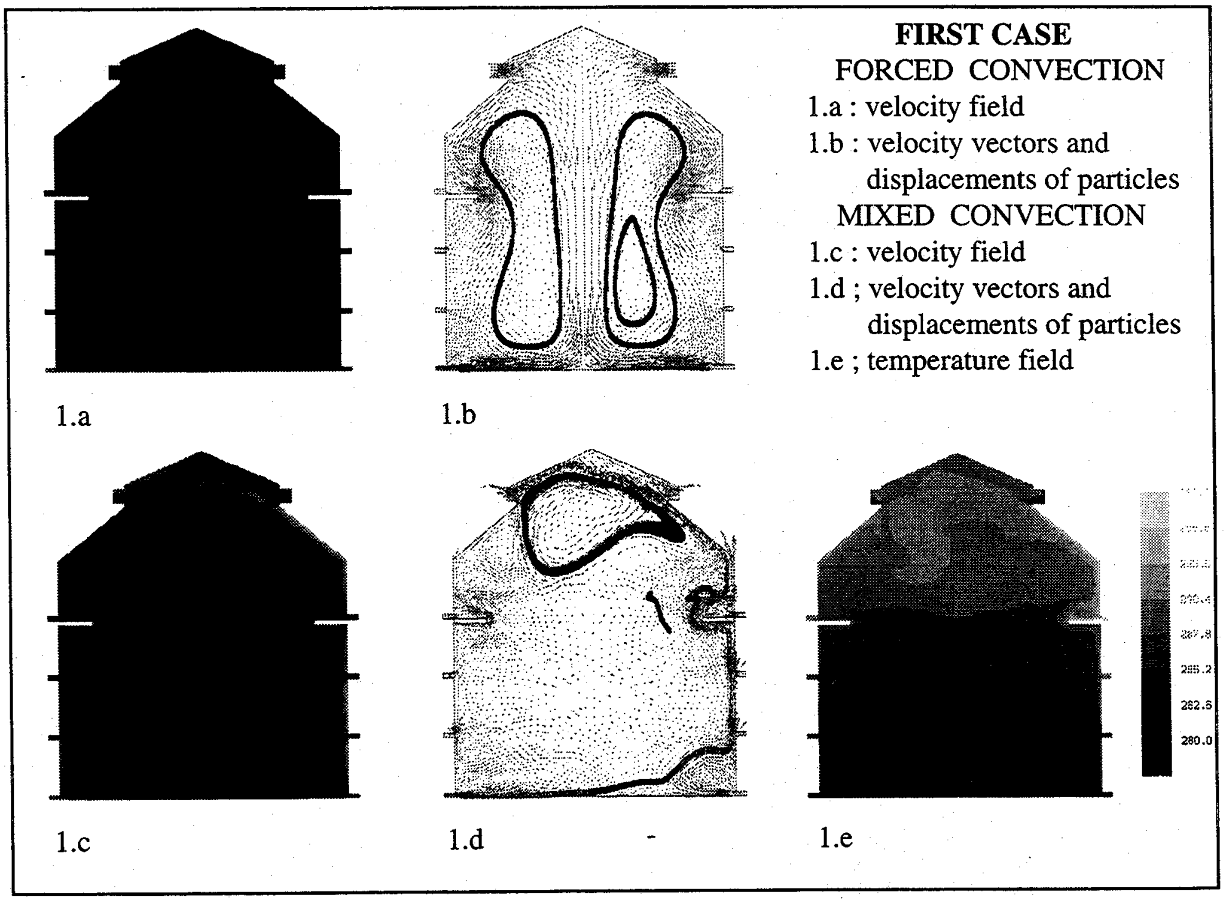


figure 0.e : COVERED STREET and BORDERING BUILDINGS



FIRST CASE

FORCED CONVECTION

1.a : velocity field

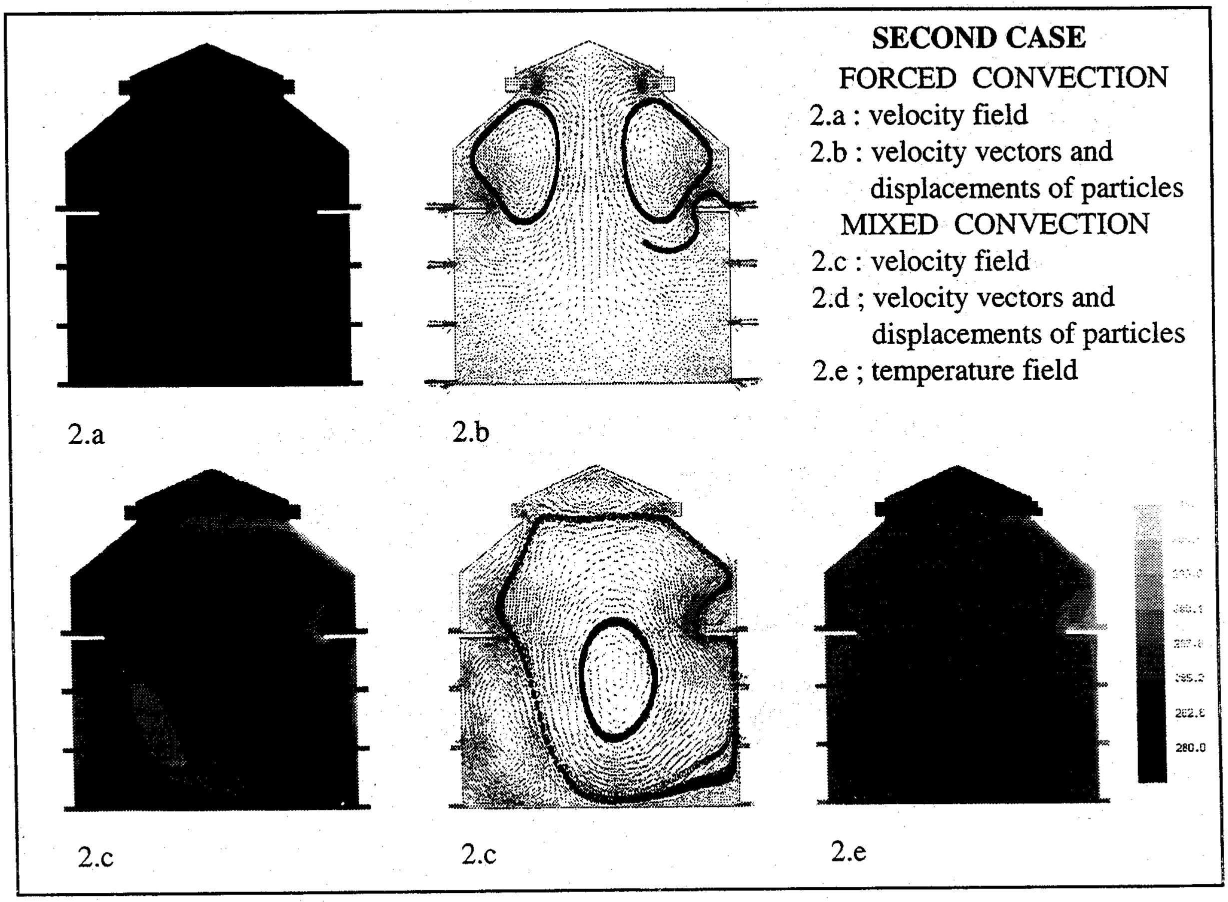
1.b : velocity vectors and displacements of particles

MIXED CONVECTION

1.c : velocity field

1.d ; velocity vectors and displacements of particles

1.e ; temperature field



SECOND CASE

FORCED CONVECTION

2.a : velocity field

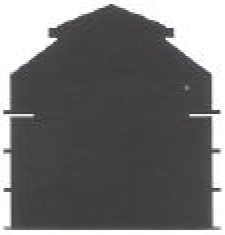
2.b : velocity vectors and displacements of particles

MIXED CONVECTION

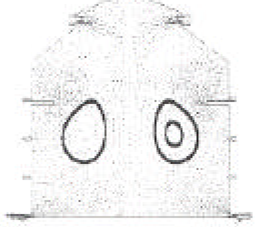
2.c : velocity field

2.d ; velocity vectors and displacements of particles

2.e ; temperature field



3.a



3.b

THIRD CASE

FORCED CONVECTION

3.a : velocity field

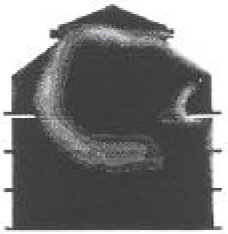
3.b : velocity vectors and displacements of particules

MIXED CONVECTION

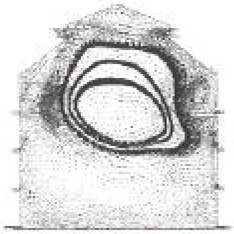
3.c : velocity field

3.d ; velocity vectors and displacements of particles

3.e ; temperature field



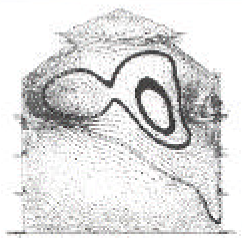
3.c



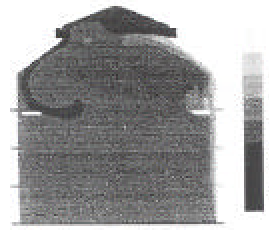
3.d

3.e

4.c



4.d



4.e

FOURTH CASE

MIXED CONVECTION

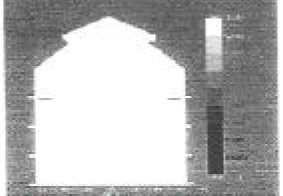
4.c : velocity field

4.d : velocity vectors and displacements of particles

4.e : temperature field

AIR QUALITY

1.f : diffusion in first case



4.f : diffusion in fourth case