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VENTILATION OF ROAD TUNNELS IN CASE OF FIRE

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ABSTRACT

The accelerated pace in construction of longer road tunnels has provoked a renewed interest in the analysis of the different scenarios that can appear during their service life. Among them one of the most complicated and worst known is the case of an accident with fire inside the tunnel. Using the powerful capacities of FIRE the paper presents a parametric study on the implications of the use of extraction ducts at ceiling (vents) as well as some of the preliminary conclusions obtained, with the numerical modelling.

1. INTRODUCTION & OBJECTIVES

A basic factor of the development of EC countries is being the establishment of a network of highways among them. The strict conditions imposed on their design to favour the fast distribution of goods and people influence the number of bridges and tunnels that have to be built. That trend induces the construction of wider and longer tunnels that are subjected to an always increasing number of vehicles.

The traffic growth is accompanied by an increased demand on comfort and safety especially in what refers to the amount of ventilation needed to maintain under control the pollution inside the tunnel as well as to the precautions needed to limit the damage and casualties that can arise during a fire inside the tunnel.

For urban tunnels where the traffic contamination and the exhausted polluted air can affect the environment, the dimensioning factor of the ventilation equipment is the "in service" situation under nominal traffic intensity. Nevertheless, the reduction in the emission of pollutants, that is a consequence of more strict regulations, has moved the balance, for the majority of cases, towards the fire scenario as the most needed of an in-depth study. As this "accidental" condition is independent of the intensity of the traffic using the tunnel, we reach the conclusion that this scenario can, in some way, be the dimensioning condition of those works.

There is a long tradition of study of that subject, that can be followed in the series of conferences organized by BHRA since 1975 (reference 1) or the recommendations prepared by the tunnel group of PIARC (reference 2). It is also interesting to see how the Administration of different countries are promoting the publication of regulations (reference 3) or technical Conferences (reference 4, 5) to examine the safety conditions during the service life of tunnels.

A trend that can be observed in the study of fires is the use of physical models either full-scale (Hacar (reference 6)) or reduced-scale (Lacroix (reference 7)) to understand the behaviour of the smokes or the devices imagined to control them. Only recently (with the advent of powerful computers and reliable fluid software) numerical modelling of fire situations has started to be used for research and it is not difficult to predict, in the future, that they will be applied routinely for the design of new tunnels.

As an example figure 1.1 (taken from reference 8) presents the evolution of pollutants on a tunnel. The fire starts in a still air situation and 5 seconds later the longitudinal fans are plugged in, until a final flow of 2m/s is established. The figure shows the plume and the fumes distribution for different instants of time (10, 30, 120, 360 and ∞ seconds).

This type of analysis is typical for a longitudinally ventilated tunnel in which the fans accelerate the air current so that all people behind the fire place can escape on foot, while those in front of the fire continue driving until they leave the tunnel, i.e.: the combustion products are forced by the ventilation to move in the same sense that the traffic. That means that the method is very effective for one way works. On the contrary, for bidirectional tunnels the procedure can not be the same. A typical approach in those case is the use of a so-called "semi-transverse" ventilation; a ceiling is established so that the tunnel section is divided in a lower zone for a traffic use and an upper zone that is used as a duct to supply fresh air through throttles regulated in such a fashion as to produce the pressure levels and to inject the air volumes suitable to reduce the proportion of pollutants to admissible levels. The tunnel is subdivided in subassemblies (cantons of say 1000m length) each of which is ventilated independently.

In case of fire the philosophy is to try to concentrate the fumes in a limited area, extracting the pollutants through controlled vents that are operated as soon as the fire is detected. For instance, let us suppose that the normal ventilation produces a longitudinal flow of 2 m/s. If 3 minutes are needed to react, about 360m will be full of smoke when the vents are opened. In order to limit their spreading two measures are taken: the opening of all vents situated in that length near the fire and the blowing of fresh air from the nearby cantons.

That general picture admits several alternatives according to different possible combinations of throttles and vents. In any case the designer has to take several crucial decisions among which are the vent dimensions, the distance between each two vents, how many vents and when have to be activated and even the nature of the measures that have to be taken to counteract the fume spreading, i.e.: There could be two options: (1) to let the longitudinal flow that maintains a certain stratification on the fumes (so that it is possible to evacuate people using the fresh air on the lower part of the tunnel) or (2) to inject fresh air that limits the fire spreading but break the stratification producing a mixing in the whole tunnel section.

This paper is a preliminary contribution to the analysis of some of these problems and to show the enormous possibilities that Computational Fluid Dynamics (CFD) offers for practical applications.

2. MODEL DESCRIPTION

The study has been performed over a tunnel with realistic dimensions (figure 2.1). The cross section has a traffic area of 51m^2 and the area above the ceiling is 13m^2. Following the PIARC recommendation the objective is the evacuation of 75m^3/s of fumes produced by a fire of about 20MW by opening the vents and blowing fresh air through the traffic area.

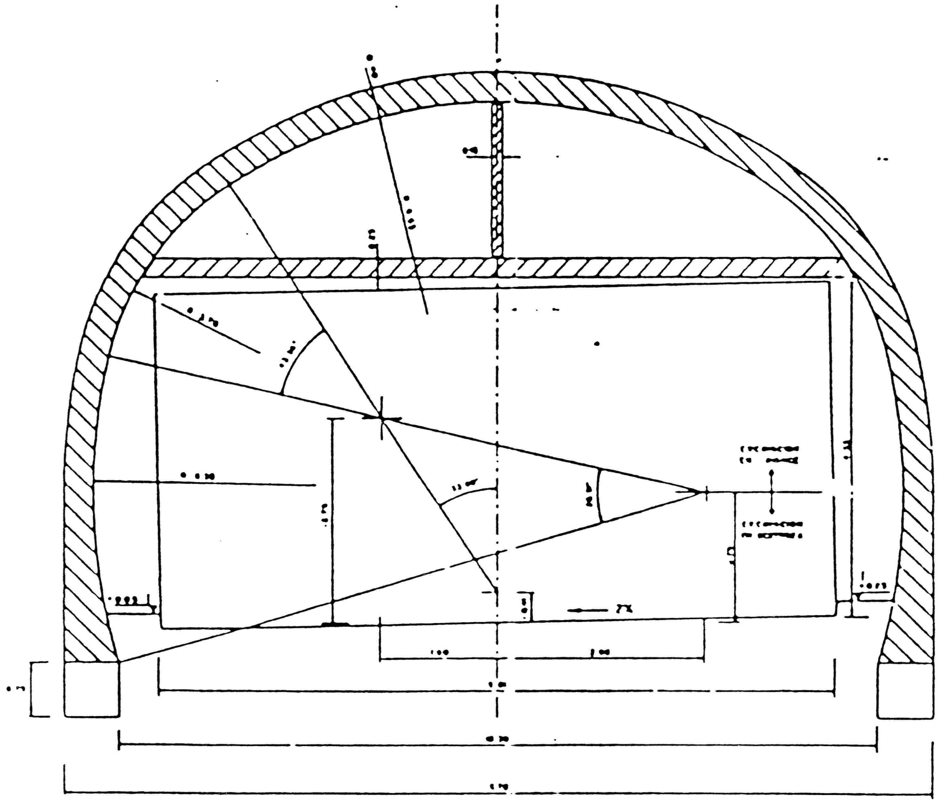

Figure 1.1. Somport tunnel cross section.

The flow is assumed to be modelled by the equations of balance of mass, momentum, turbulent kinetic energy and rate of dissipation of it, using a closing model of the k-epsilon type. Another equation is used to model the mixture of two different gases: air and combustion products. The proportion of both components is represented by an additional variable called the passive scalar. This variable takes the value of 0 for pure air and 1 for only combustion products (smoke). For simplicity in this preliminary analysis, we asume the same fluid properties for air and smoke.

The fire area is 4m^2 and it is on the tunnel floor. Several different sites have been studied but only the results corresponding to its situation in the axis of the tunnel between two vents will be shown. If the velocities of the generated smoke is 15m/s the emitted rate volume is G_r=60m^3/s and assuming an absolute temperature of 1400K the power is $Q \approx 25MW$, which is in the order of magnitude recommended by PIARC for an accident of a bus. In order to reduce the numerical effort only the traffic area has been modelled and the vents have been reproduced adding small chimneys to create a developed flux. Models of different lengths have been used depending on the objectives. For instance, figure 2.2 shows the cells used in a model of 300m with vents of 2,5x0,75m^2. That model was built using 24.000 cells. In this case the model did not included the throttles because a previous study with a shorter (50m) model showed that the flux was mainly controlled by the vent during the extraction period, even in the absence of the fire as can be seen in the figure 2.3(b) showing the vertical velocities isolines on a horizontal section of the tunnel.

3. PARAMETRIC STUDIES

Two main models have been built. In one of them (figure 2.2) it is assumed that as soon as the fire is started the vents are opened. In this case, the objective is to obtain the effectiveness of the different vents depending on their distance to the fire focus.

In a second model the length has been extended to 600m and three sequential steps have been computed: in the first a longitudinal flow of 2m/s is created. When the steady state situation is reached the fire starts and during 3 minutes the fumes extend along the tunnel. Then, the vents are opened and air is injected through both ends of the tunnel to counteract the flux.

This second model reaches almost 50000 cells and many time steps are required to mantain a good CFL parameter during all the simulation time.

3.1. Instantaneous vent opening

In this problem, to force the flux, both ends of the tunnel are subjected to the same pressure (1 bar) while in the end of the chimneys a suction of 250Pa has been imposed. After around 1,5 minutes the steady-state conditions have been reached. Figures 3.1, 3.2 and 3.3 show the fume concentration. In 3.1a it is clear that only the nearest two vents are active in the evacuation procedure. Figure 3.2 shows the plume over the fire as well as the stratification in a section between the fire and the first vent. In figure 3.3a it is possible to see the concentrations under the second vent, with two areas of high smoke level in the corners that probably would disappear if the throttles located in that area were actuating. Figure 3.b, which is a view from the top, shows again the limitation of the fume extent.

The main conclusions that can be obtained from this study are that the pollutants are confined to the space between vents and that the further vents exhaust the clean air that is entering through the tunnel ends. The speed of the air through the vents is relatively high (over 24m/s), so it seems advisable either to reduce the distance between vents or to increase their dimensions.

To analyze the first possibility a new model was built reducing the distance between vents to 50m. A sample of the results that where obtained is included in figure 3.4. Figure 3.4a is a general longitudinal section while figure 3.4b is a close-up of the fire area. As it can be seen, there are now 4 vents that are active in the evacuation process. The ratio between the smoke extracted and produced is called "effectiveness". From left to right these effectiveness are respectively 12%, 24.5%, 31.3%, 11.2%, 0% and 0%; i.e.: only 200m are really effective in the process of smoke evacuation, so only four vents should be opened.

3.2. Delayed vent opening

As explained above in this case a more realistic scenario has been attempted. Fist of all, a tunnel length of 600m has been discretized containing 5 vents separated 100m each. An initial computation has allowed the establishment of a current of 2m/s that is considered representative of an in-service situation. Then, the fire is activated between the first two vents (figure 3.5).

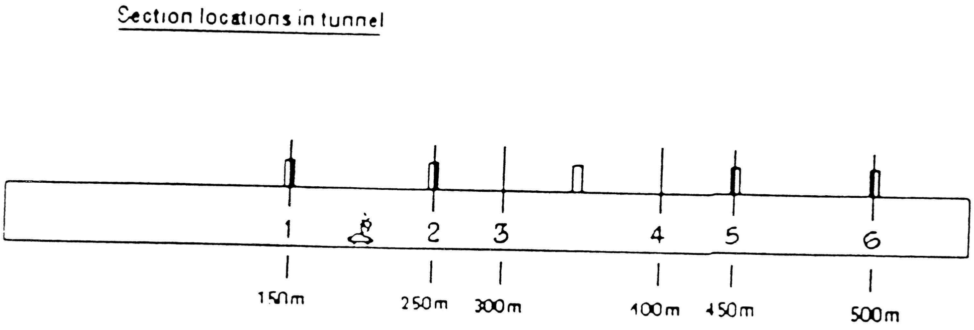

Figure 3.5.

For 3 minutes the smoke fills the tunnel and then all vents are simultaneously opened and a counter current of air is established to limit the fumes extent at both ends of the tunnel. Figures 3.6.a and 3.6.b show respectively the evolution of the total smoke concentration in the tunnel and the average temperature along the time. As can be seen to a practically linear increase follows a smooth decrease after the vents are opened, showing that after about 1,5 minutes practically a steady-state solution is reached, which is similar to the results obtained in the previous cases.

The effectiveness of the different vents can be imagined analysing the curves plotted in figure 3.7 where the smoke concentration evolution is showed for different locations in the tunnel (see figure 3.5).

It is clear that the sudden increase in sections 2 and 3 are due to the important role played by vents near the fire in the suction process. On the other hand, section 5 remains stationary as if the fact of opening the vents did not affect the effectiveness, while chimney 6 clearly shows a reduction. Chimney 1 contributes seldom to the smoke evacuation. That means that only the down-wind vents are effective, and that at most only 3 vents (i.e.: 200m) need to be opened.

4. CONCLUSIONS

The paper tried to show how effective is the numerical treatment in a problem of practical importance for which the recommendations contained in current Codes are not completely substantiated neither by experience nor by analysis.

Although the computational effort is large, it is possible to detect the effectiveness of the proposed procedure and, in the future, the model will be subjected to varied boundary conditions in order to detect what can be the best philosophies for the "in service" exploitation of the tunnels.

About the particular problem tackled in the paper, it is clear that the current assumption of opening all the vents contained in a length of 500m does not introduce any advantage over the opening of only the couple of vents nearer to the fire place. It seems also that a distance of 100m between vents is not an optimum, and it should be better to reduce the distance to 50m in order to obtain a faster smoke evacuation.

On the other hand, the running of the large model has shown that although the vents are very effective, the impulsion of air from the ends of the tunnel destroys the smoke stratification what is an undesirable feature in face of the users safety.

5. ACKNOWLEDGMENTS

This paper was possible thanks to the encouragements received from the engineers Rafael López and Fernando Hacar from the Spanish Ministry of Public Works.

It is fair also to recognize the interest shown by INGECIBER (and specially by his director Eng. Mr. M.A. Moreno), helping with his expertise and even with its hardware to the long runs necessary for the results.

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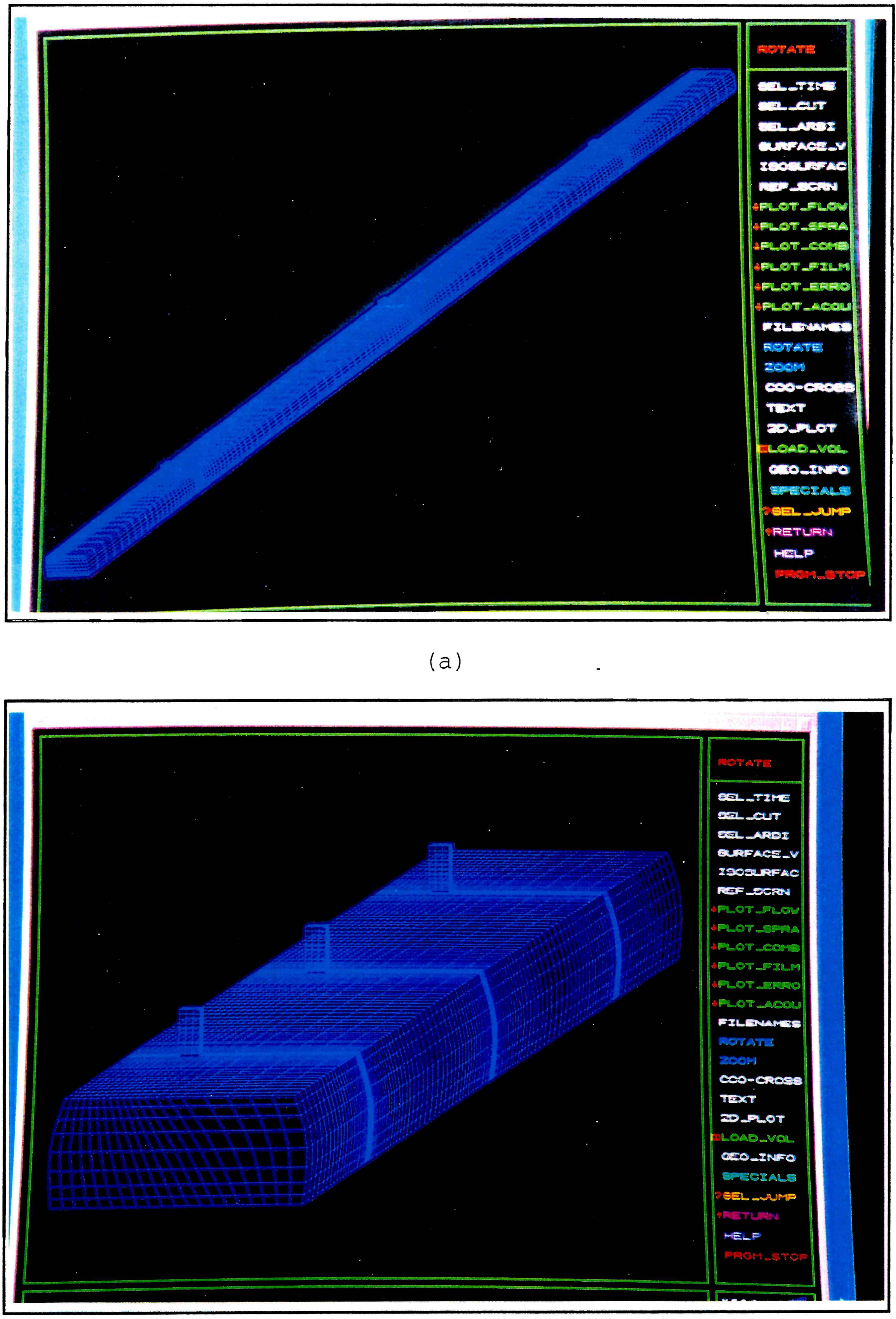
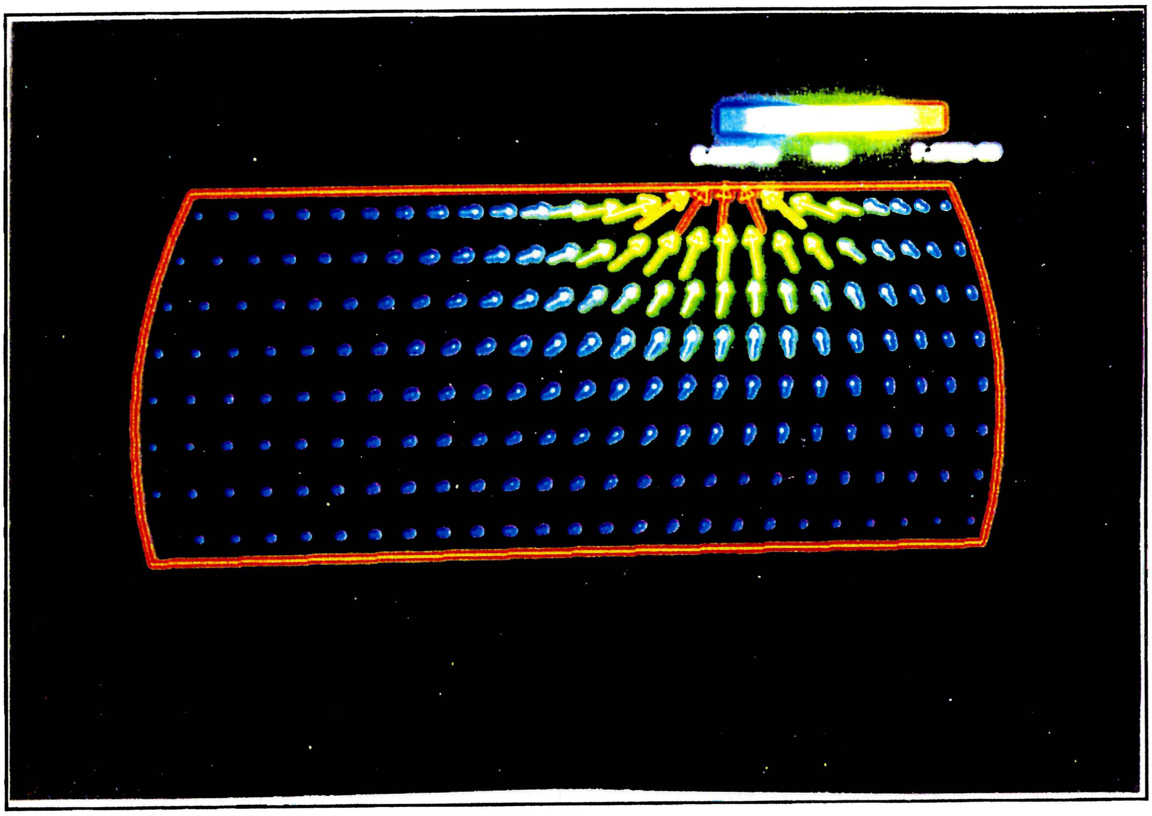


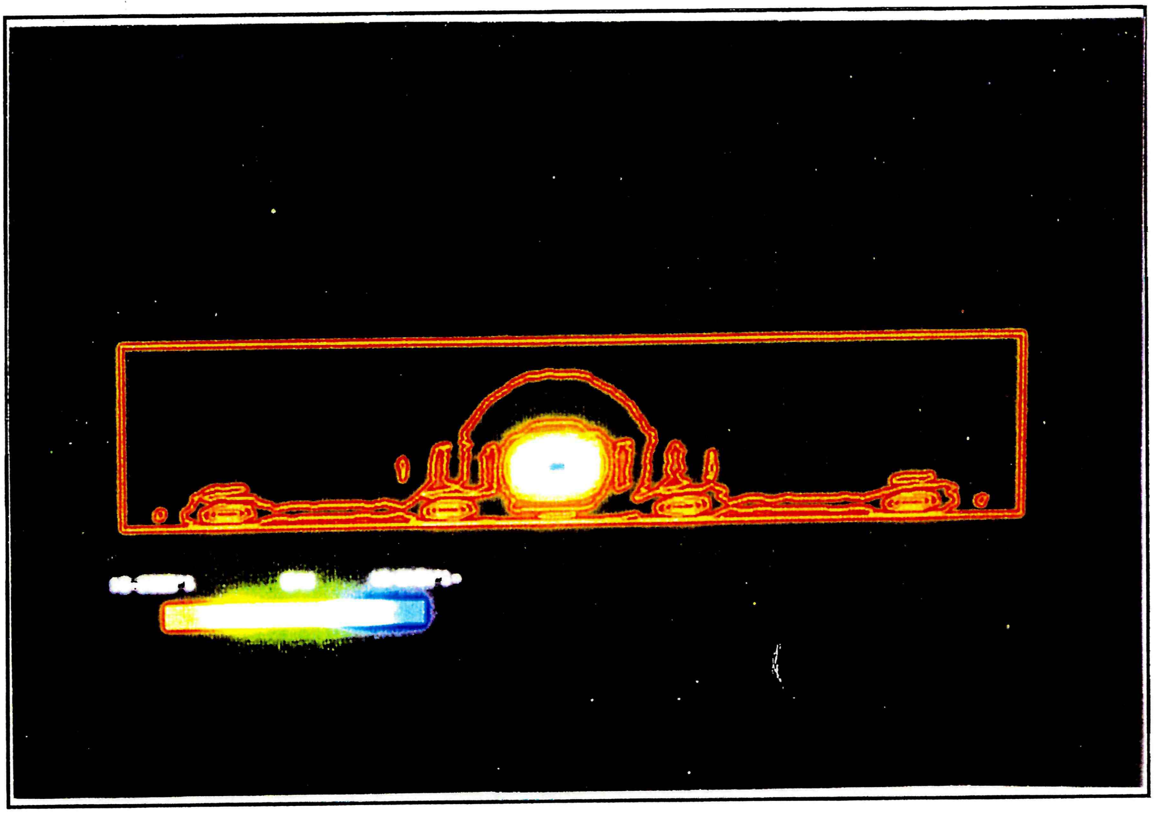
(a)

(b)

Figure 2.2 Model of the studied domain

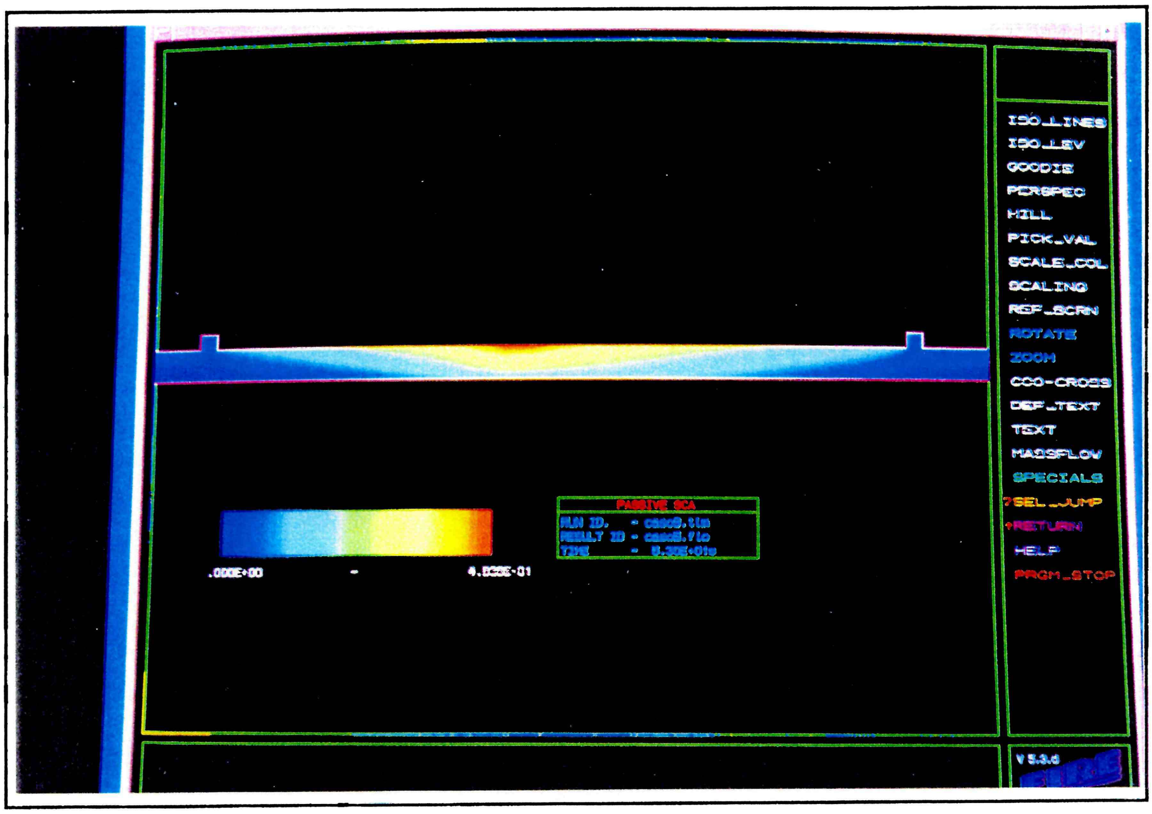


(a) Cross velocity on vent section



(b) Velocities isolines on a horizontal section

Figure 2.3



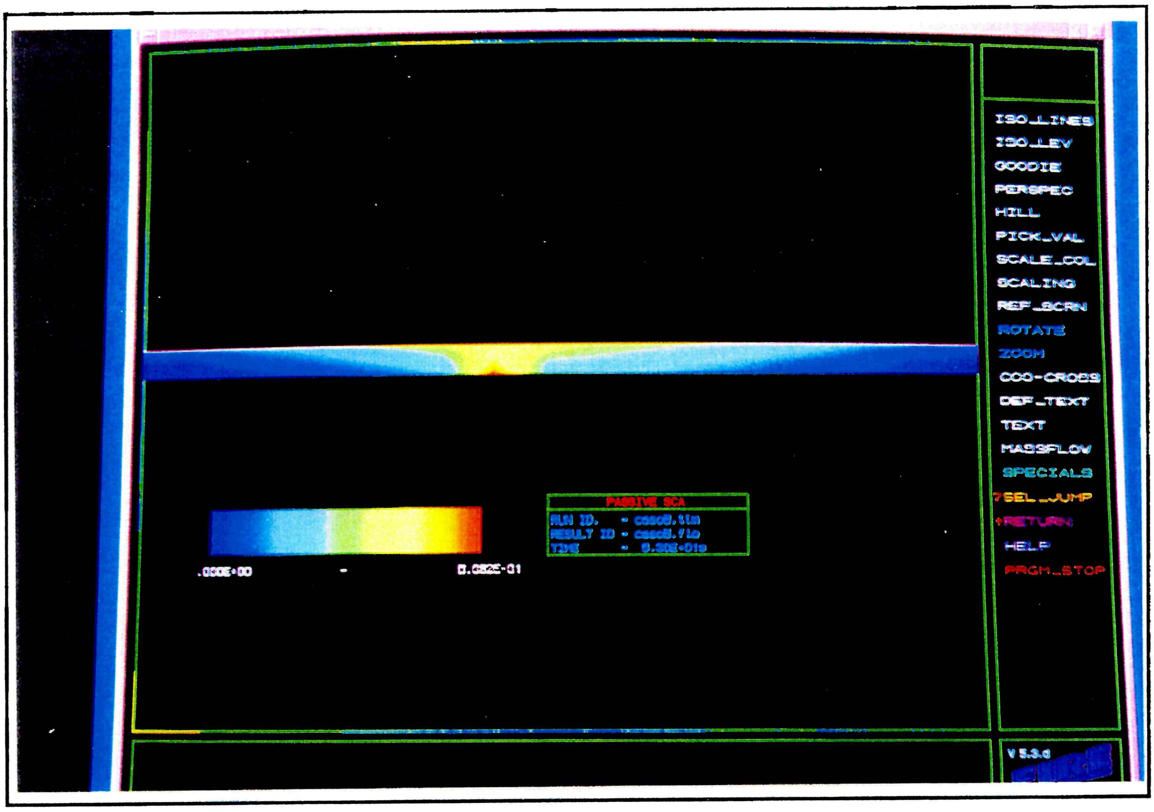
PASSIVE SCA

RUN ID. - caso8.tim

RESULT ID - caso8.flo

TIME - 8.30E+01s

(a) Fumes concentration under vents



PASSIVE SCA

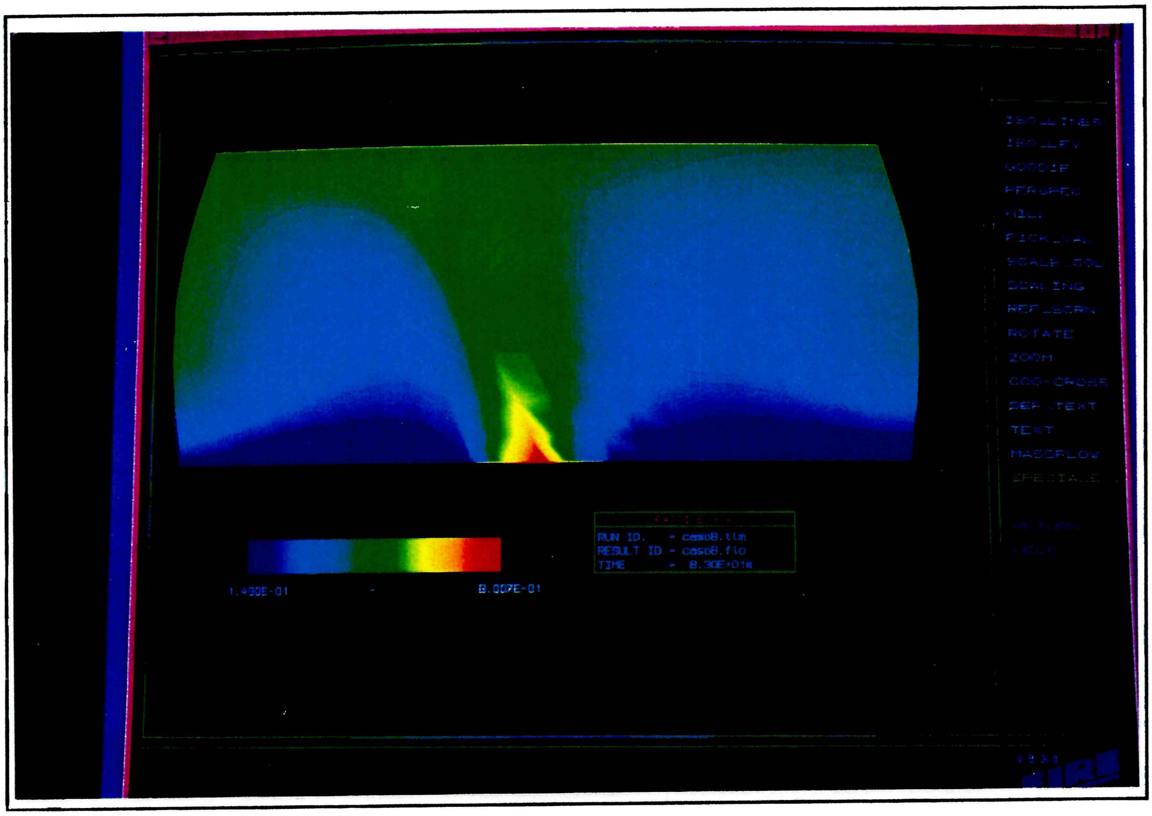
RUN ID. - caso8.tim

RESULT ID - caso8.flo

TIME - 8.30E+01s

(b) Fumes concentration detail on axis tunnel

Figure 3.1



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RUN ID.    - caso8.tlm
RESULT ID  - caso8.flo
TIME       -  8.30E+01s
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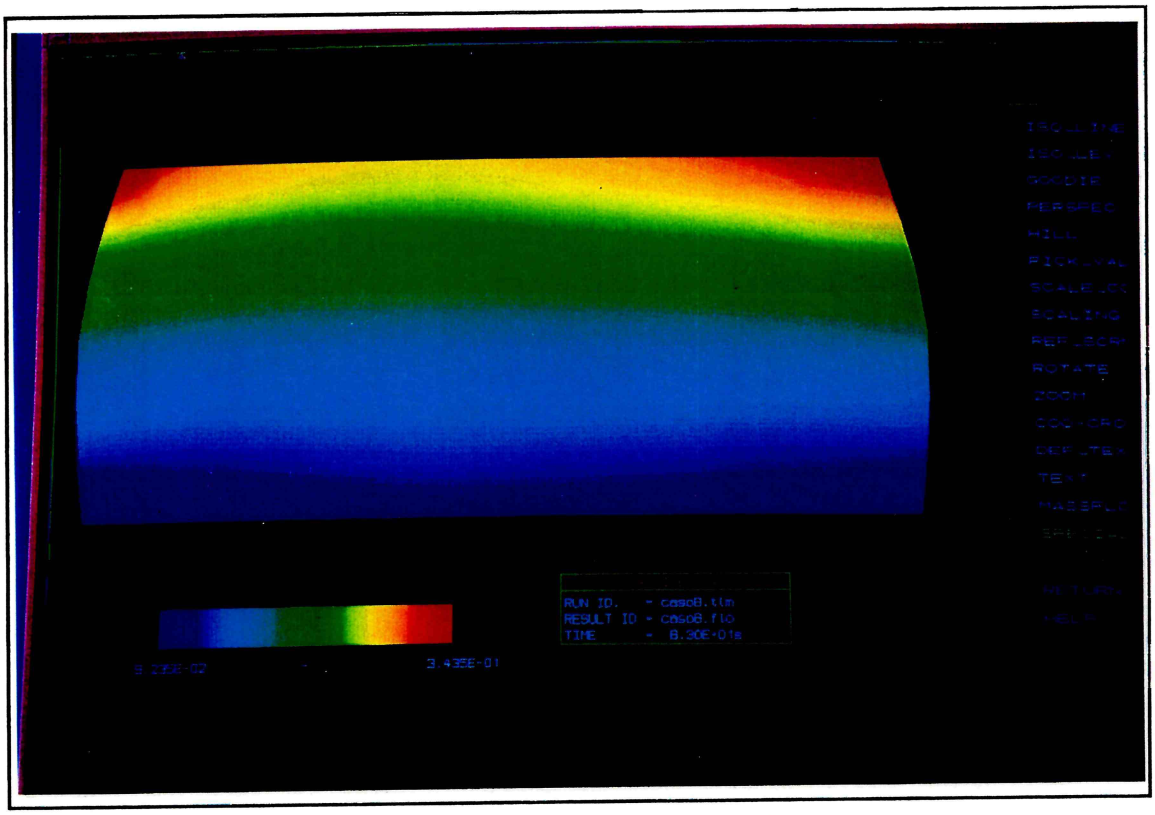
(a) Concentration on fire location



```
RUN ID.    - caso8.tlm
RESULT ID  - caso8.flo
TIME       -  8.30E+01s
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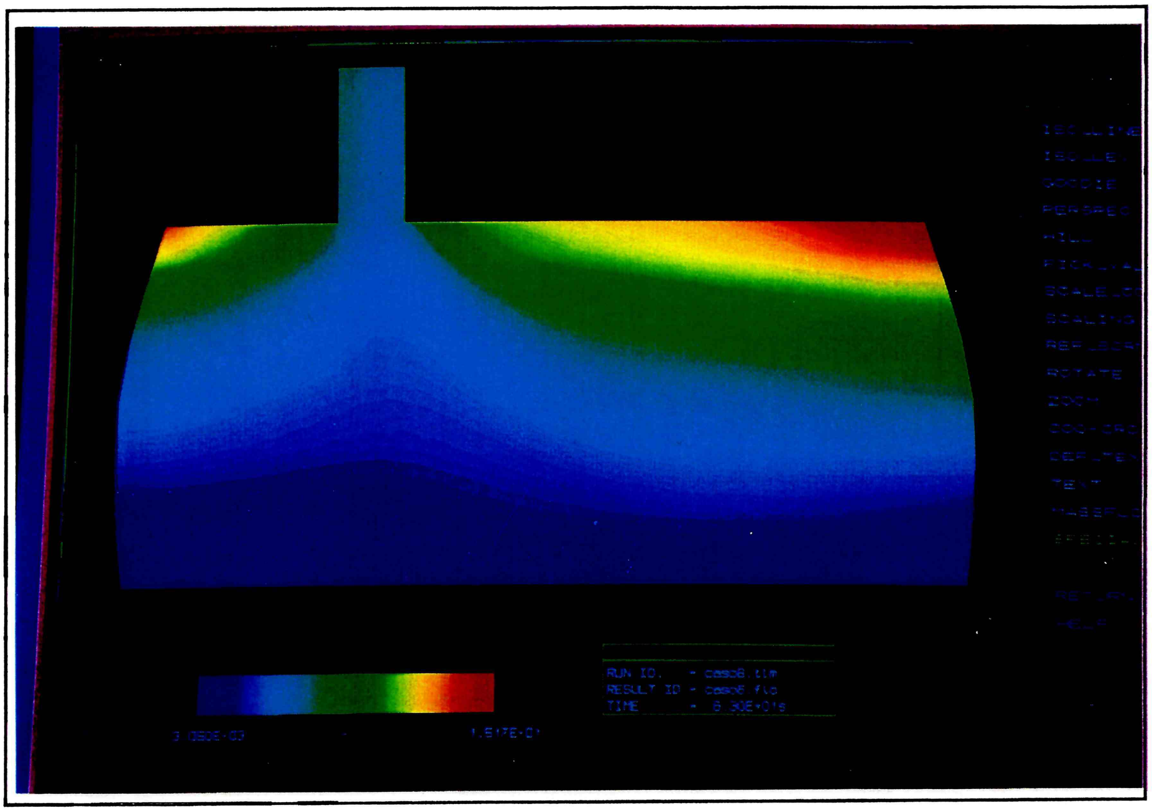
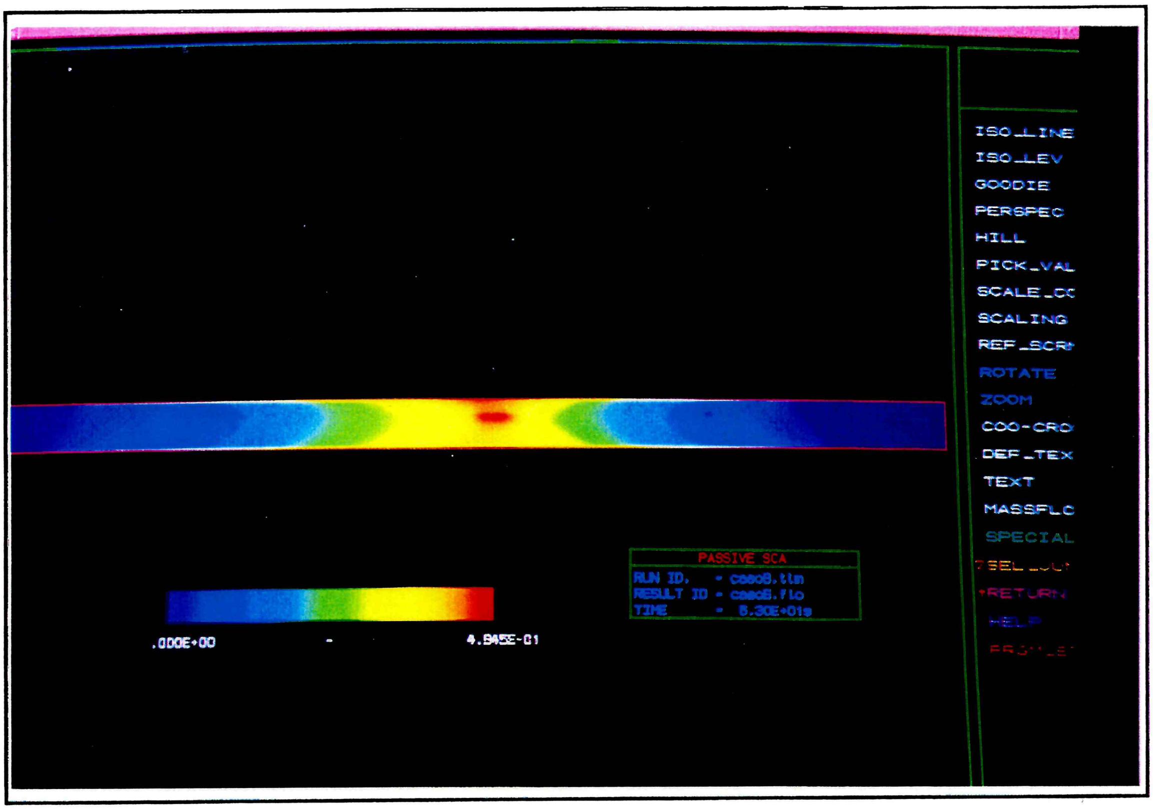
(b) Concentration 25 m far from the vent

Figure 3.2



RUN ID. - case8.tlm
RESULT ID - case8.flo
TIME - 5.30E+01s

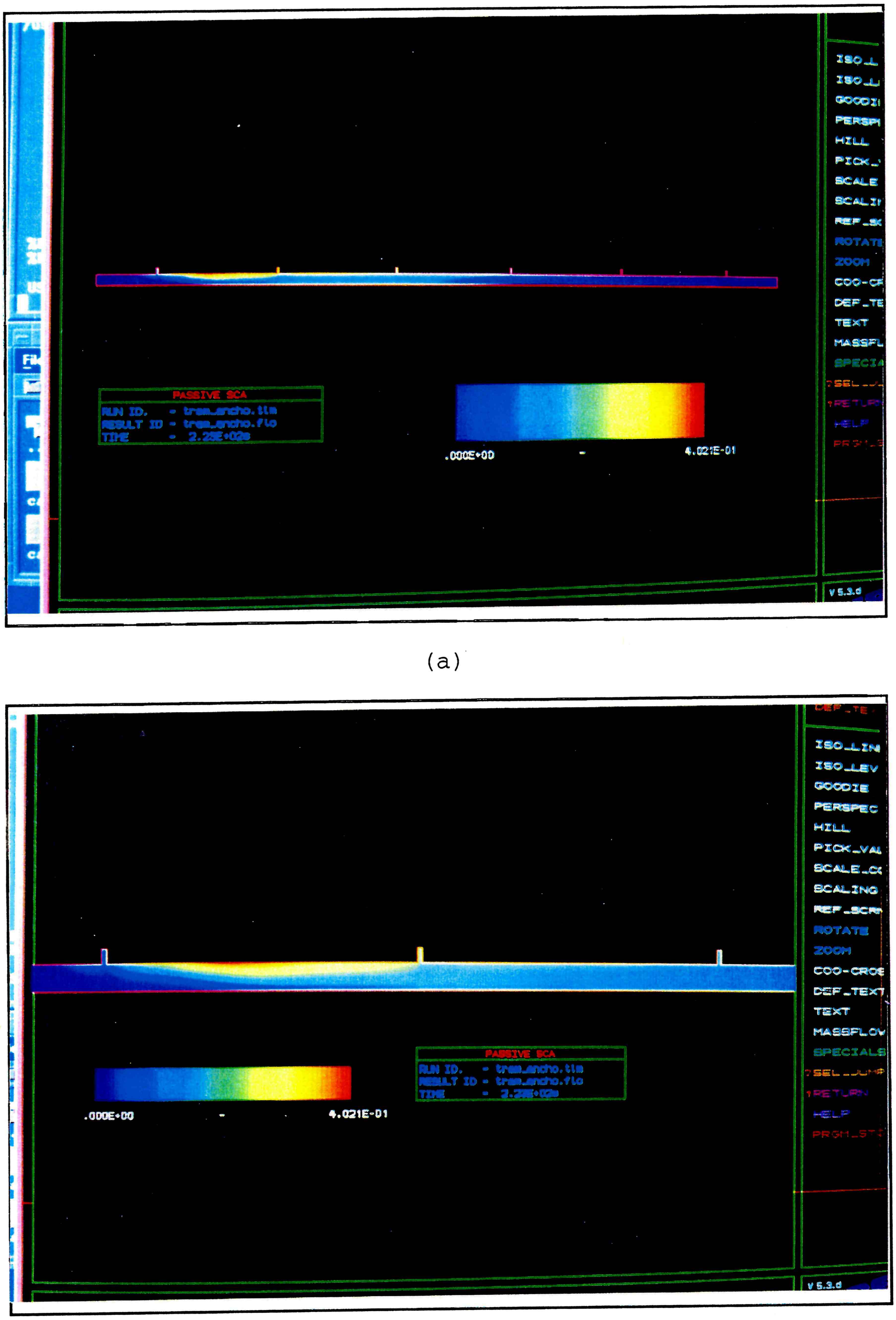
(a) Concentration on vent section



PASSIVE SCA
RUN ID. - case8.tlm
RESULT ID - case8.flo
TIME - 5.30E+01s

(b) Plant distribution. 4 m high

Figure 3.3


PASSIVE SCA

RUN ID. - tram_ancho.tim

RESULT ID - tram_ancho.flo

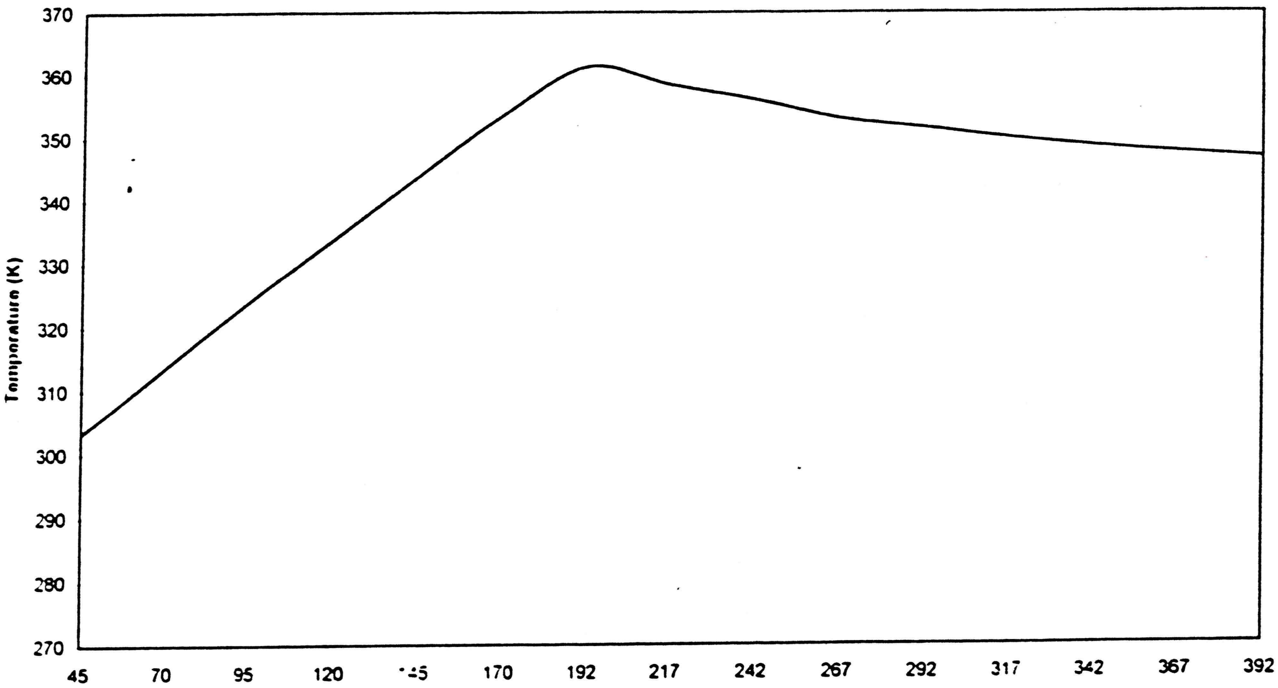
TIME - 2.25E+02s

(a)

(b)

Figure 3.4 Fumes concentration for vents 50 m apart

Average temperature in tunel



Time history of smoke distribution
600 m model

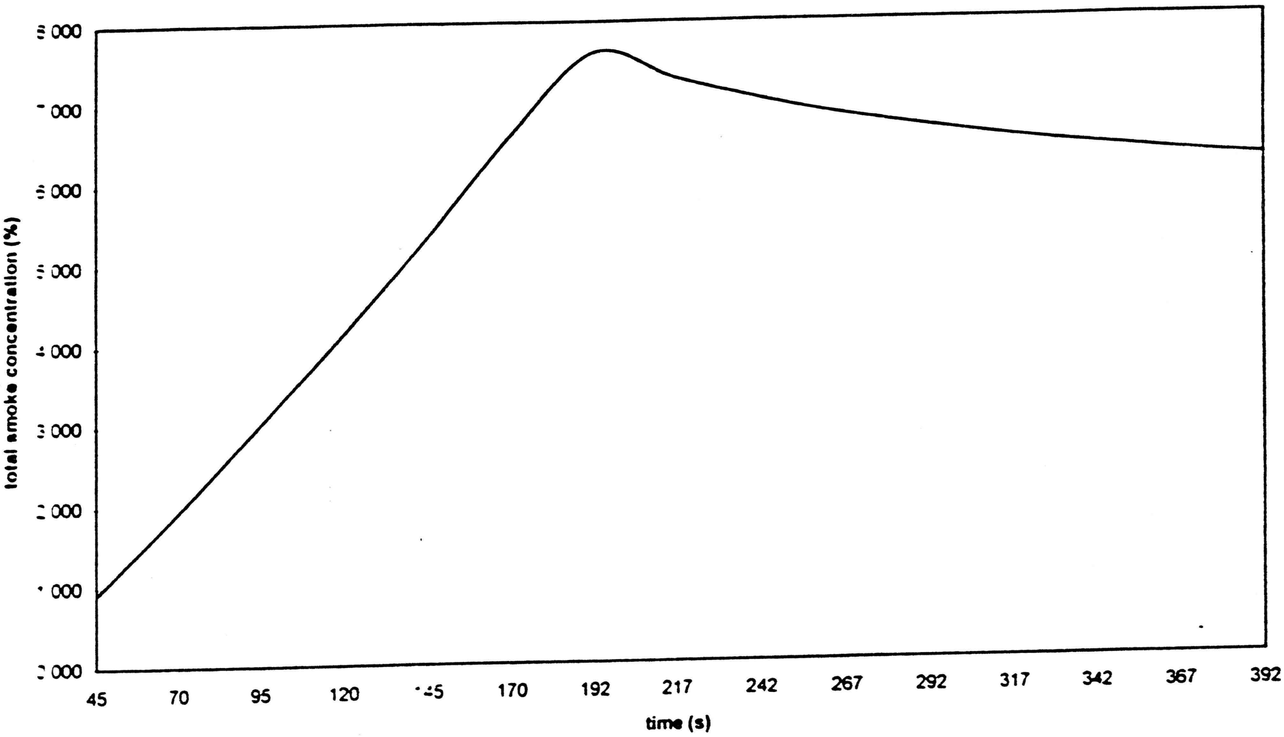


Figure 3.6

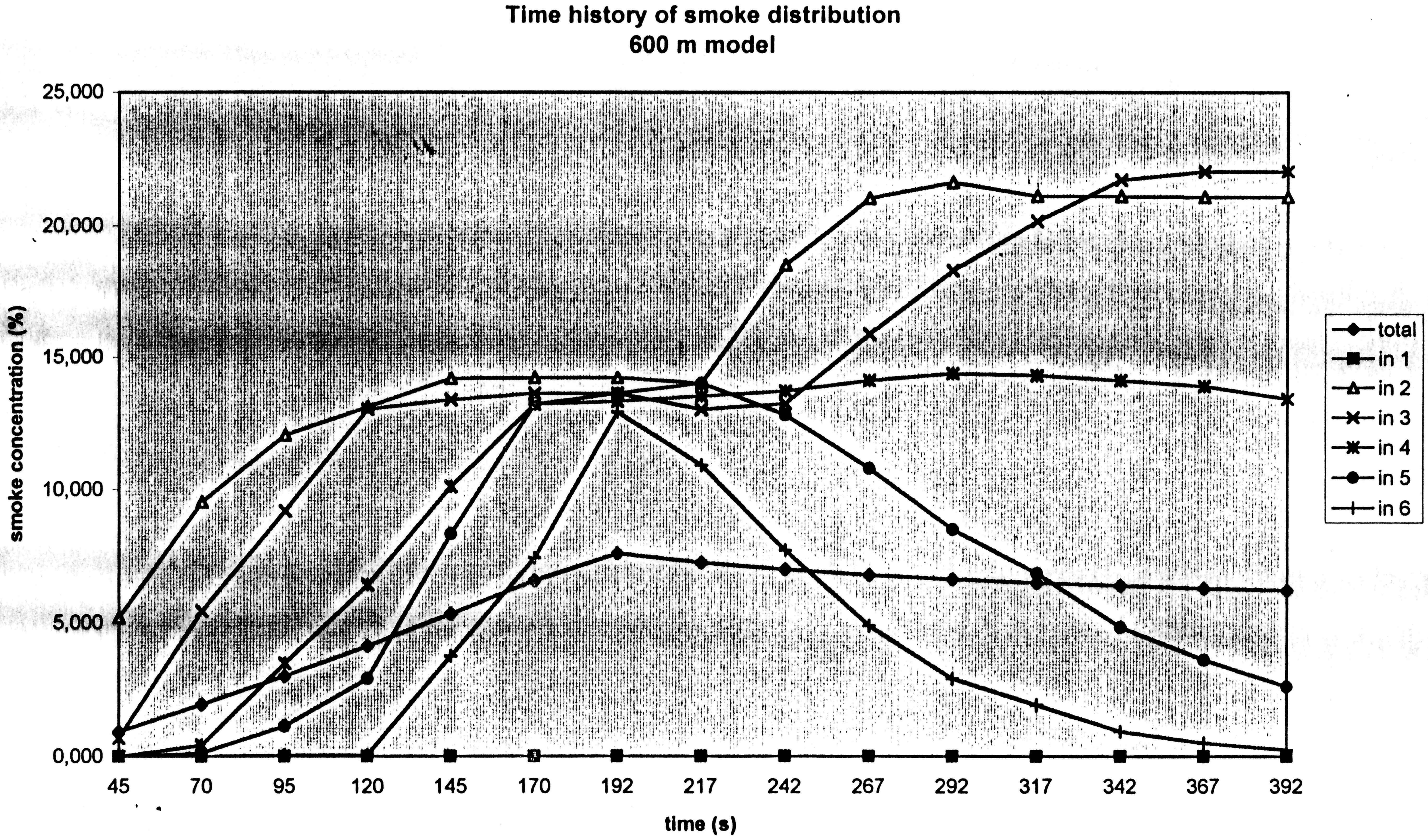

Time history of smoke distribution
600 m model
smoke concentration (%)
25,000
20,000
15,000
10,000
5,000
0,000
45
70
95
120
145
170
192
217
242
267
292
317
342
367
392
time (s)
total
in 1
in 2
in 3
in 4
in 5
in 6

Figure 3.7