Investigation of Fire-Induced Smoke Movement in Tunnels and Stations: An Application to the Paris Metro

J. P. VANTELON, A. GUELZIM and D. QUACH
Laboratoire de Chimie Physique de la Combustion
Université de Poitiers
Domaine du Deffend, F-86800 Mignaloux-Beauvoir, France

DOAN KIM SON
Laboratoire de Thermique
Ecole Nationale Supérieure de Mécanique et d'Aérotechnique
20 rue Guillaume VII, F-86034 Poitiers, France

D. GABAY and D. DALLEST
Régie Autonome des Transports Parisiens
127 Avenue Ledru Rollin, F-75011 Paris, France

ABSTRACT

The behaviour of fire-induced smoke layers in a tunnel and a particular station of the Paris Metro, in the presence of ventilating-air flow, is experimentally investigated using small scale models. For practical purposes, laser investigation techniques are utilized. The reverse layer formed near the ceiling of a tunnel, and flowing against the ventilation, is analyzed from the results of the small scale test as a function of the fire source power and ventilation current. A simple modelling procedure is applied which should permit full scale lengths of reverse layers to be deduced. Measurements of temperature distribution, along the tunnel median plane and cross sections, reveal the stratified evolution of the smoke backflow. The experiments with a ventilated tunnel-station configuration show the essential characteristics of the smoke movement (entrainment, stratification, recirculation, etc...). The propagation of hot combustion products, indeed, is of practical importance for fire-fighting and people evacuation.

Keywords : Fire problems in transportation. Fire plumes. Smoke behaviour. Modelling procedure.

INTRODUCTION

Since the construction of the Metro of Paris began, in the 1900's, problems of comfort and hygiene have been continualy taken into consideration. In the course of the equipment evolution, particularly the installation of increasingly higher performance railway materials, the systems insuring hygiene have been adapted accordingly. However, since the 1960's, the use of materials with pneumatic bearings, the creation of the Reseau Express Regional (RER) with an important programme of new design of the stations (with more escalators and lighting systems), have produced a significant enhancement in power consumption and, in consequence, added waste heat.

In order to take care of the potential consequences on bioclimatic comfort, a vast programme to install ventilation equipment was undertaken. This has resulted in the existence of more than 200 ventilators and 300 air shafts in the underground railway network, equipment known as "de confort".

Nevertheless, in addition to obtaining suitable climatic conditions, it appears that all these installations could be used to extract smoke in the event of accidental fires in tunnels or stations. Fires in tunnels, indeed, present some serious problems, as the heat, the smoke and the toxic products resulting from combustion, are not diluted in the atmosphere but are trapped in it, forming an obstacle to fire brigade intervention and evacuation of people. Studies were then performed to utilize rationally the existing fans. This implies one should :

- produce a list of characteristics of the ventilators, in each location, to be used to establish procedures
- determine their behaviour and endurance as a function of the temperature level
- investigate the characteristics of the smoke flows (backlayering, entrainment, stratification, recirculation) in tunnels or adjacent stations, as a function of the fire power and ventilation speed.

Studies concerning this last point are developed jointly, on the one hand by the "Laboratoire de Chimie Physique de la Combustion" and the "Laboratoire de Thermique" of the University of Poitiers, on the other hand by the "Régie Autonome des Transports Parisiens" (RATP), and some resulting experimental investigations are presented here.

SMOKE MOVEMENT IN TUNNELS UNDER THE EFFECT OF VENTILATION

Smoke evacuation by extraction is the most classic method as it reduces turbulence. Under the effect of ventilation, flames and plumes are deflected and the smoke is drawn downstream from the source. Nevertheless, with moderate extraction speeds and if the fire is sufficiently powerful, the smoke can return upstream underneath the ceiling, to form what is called a reverse layer, countering the effect of ventilation. One is therefore in the presence of stratified flows in the form of two currents (air and smoke) moving in opposite direction.

1) Background

Numerous experimental and theoretical studies have been carried out, during the past thirty years, seeking to define the behaviour of thermally generated stratified layers in tunnels fires in the presence of ventilating-air flow. EISNER and SMITH (1) reported that a countercurrent flows back from the fire until its buoyancy is reduced by heat loss to the strata or to the air beneath. THOMAS (2) (3) has shown that backing occurs if the ratio of the buoyancy head to the velocity head is greater than unity. DE RIS (4) analyzed fuel-rich fires spreading within ventilated fuel-lined ducts in terms of overall energy balance and discussed the conditions for the occurence of these hazardous fires and the preceding criterion for backflow. ALPERT (5) analyzed an outward moving ceiling jet produced by a hot gas plume generated by a floor-level fire. He showed that a simple entrainment model is able to predict the jet behaviour. HWANG et al (6) were the first to analyze theoretically reverse stratified flows in duct fires in the presence of ventilation. A two- dimensional model is developed predicting the length of the reverse layer as a function of ventilation speed, duct inclination, mass flux of fire plume, etc., the unknown constants introduced being determined from the experimental data of EISNER and SMITH (1). LÉE et al (7) examined the response of the blower-driven ventilation flow to a duct fire. NEWMAN (8) related its experimental data for stratification to Froude number. Other attempts using models were carried out by KUMAR and COX (9) and HWANG and WARGO (10) which elucidated the behaviour of the rising hot plume from a simulated fire source in a ventilated channel.

Due to the serious danger represented by a fire in a tunnel, it is practically difficult to envisage large scale experiments to test procedures for evacuation and for the removal of smoke. Knowing that many engineering problems could be solved in a satisfactory way by applying to real cases scale modelling procedures established on a laboratory scale, we decided, in a first approach, to study this phenomenon of smoke movement against the ventilating air flow, on a small scale model. The required condition is that there is a similarity between the scale model and the system considered in full scale. Scaling the model is obtained by identifying the major parameters of the systems and expressing these in the form of relevent dimensionless groups which must be preserved for small and full scale systems.

2) Experimental set-up

● <u>Description of the scale model</u>

The scale model used satisfies several operational criteria :

- the laser investigation techniques used require that it be built of transparent material
- the material chosen must also be able to resist the high temperatures encountered near the heat source
- the dimensions of the structure must be such that the ends do not notably influence the smoke behaviour.

This scale model is made of two shells of thermoresistant borosilicate glass (pyrex), 0.95 cm thick, in half-cylindrical form, with an inside diameter of 30 cm and 150 cm in length. Placed end to end, they form a tunnel 3 m long (figure1). It is positioned on a kerlane plate which ensures a good thermal insulation. Thus, we avoid any possible heating of the air moving in the lower part, through conduction of the heat from the heat source. The heat source is a small porous burner, 2 cm

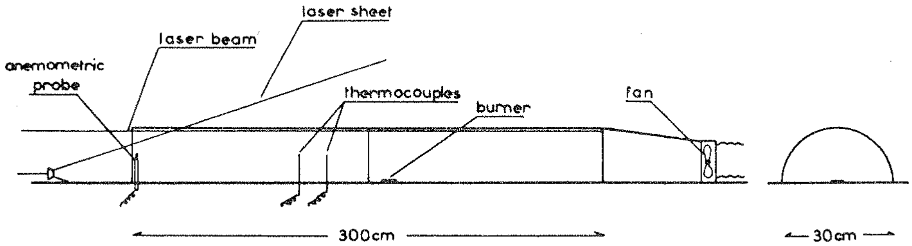


FIGURE 1 Schematic of the tunnel scale model

in diameter, located in the middle of the tunnel, in its median plane. Its supply rate, regulated by a rotameter calibrated for the operational conditions, is variable, permitting work to be carried out with different powers. The ventilation flow is obtained with a fan having variable rotation speed, placed at one end of the scale model and working by extraction. The maximum ventilation speed available at the opposite end is of the order of 25 cm s^{-1}.

- <u>Investigation techniques</u>

To show the smoke entrainment and the flow stratification, laser visualisation is used. Two approaches can be envisaged :

- a low power laser beam (10 mW) can be moved in the median plane of the tunnel, perpendicular to its base. The beam is made visible by scattering of the particles present in the smoke, which play the role of a tracer. This permits measurement of the length of this smoke layer, at different distances from the base of the tunnel and, subsequently, the location of the interface between the two layers of fluid, fresh air and smoke, moving in opposite directions.
- a beam of a stronger power laser (5 W), passes through a divergent lens which expandes it to create a laser sheet in the median plane of the tunnel. The plane may then be observed, either directly or by means of classic photography or video.

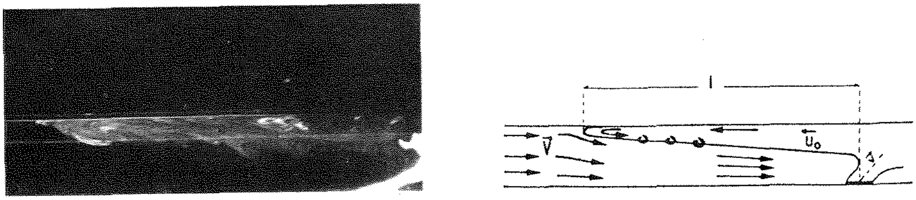
The temperature measurements are performed with chromel-alumel thermocouples of 50 µm wire diameter. These thermocouples are introduced in the tunnel through the floor and positioned normally to it. The output signals are fed to a high-gain DC amplifier (1000:1) and then to an analog/digital converter. The digital signals are sampled and stored by a PDP 11/:03 minicomputer. The measured temperatures are time averaged.

The speed measurements are carried out with an anemometric probe DISA type 54 N 50. The profiles are determined at the end of the tunnel, on the opposite side of the ventilation system, in the median plane, and then integrated.

3) Results

The first tests consisted of verification of the reliability of the scale model and observation of the flows' steady state for the experimental conditions of interest. The observations carried out using visualisation showed the principal characteristics expected and encountered in the bibliographic review. In the presence of ventilation, the smoke plume bends and is entrained by the current created.

Nevertheless, in some conditions where the fire is powerful and the ventilation is weak, a reverse layer flows against the longitudinal air current (figure 2). The interface between the layers of smoke and air is inclined and is thicker towards the source.



a) b)

FIGURE 2 Reverse layer of fire-induced smoke against ventilation current. a) Layer sheet photograph in the median plane of the tunnel - b) Sketch showing vortices and rolling structures at the interface between the two opposite currents (air and smoke) and also notations of the considered parameters.

The inclination is due in part to a cooling of the smoke as it moves away from the plume, and which then finds itself re-entrained by the flow of fresh air. The length and thickness of the reverse layer increase with the thermal strength. Its initial velocity depends on the speed of the hot gases inside the plume. A more powerful source allows the reverse layer to reach further into the tunnel. At the nose of the reverse layer, the longitudinal velocities are cancelled and a corner effect may be observed where the layer of fresh air meets the hot layer of smoke, slides under the latter and accelerates due to the shrinking of the cross-section. The shear stress at the interface is important and generates turbulent zones which act as transversal rolls, making it easier for the layers to slide one on top of the other (figure 2). It may also be noted that the penetration of the reverse layer is made easier by the deficit of velocity at the wall.

The use of the laser beam, located in the median plane, under and parallel to the ceiling, allows us to study the evolution of the reverse layer length as a function of the two parameters of major interest : source power and ventilation speed. For a given power, the layer length is measured for different ventilation speeds. This operation is then repeated for several strengths. The results obtained are presented in figure 3. Note that the rates of heat release are corrected of radiative losses (40% measured in situ). For a given ventilation speed, the length of the reverse layer increases with the rate of heat release of the source but the curves bend due to the simultaneous increasing of shear stress and re-entrainment at the interface between smoke and fresh air. These results can be used to apply a modelling procedure. In this configuration, turbulent conditions can be considered as predominant and viscous effects neglected. The driving force is then generated by convective flows created by the flame and the fan. If the fire is represented by a point buoyancy source and if a conventional Froude scaling is applied, the following correlation can be obtained :

$$\frac{l}{R} \propto \left(\frac{g \dot{Q}}{\rho_\infty C_p T_\infty V^3 R} \right)^n$$

where l is the length of the reverse layer, $\dot{Q}$ is the rate of convective heat release from the fire, g is the gravitational acceleration constant, ρ_∞ is the ambiant density, C_p is the specific heat, T_∞ is the ambient temperature, V is the ventilation speed and R is the radius of the tunnel.

To use it, it is necessary to know exponent n. The results presented in figure 3 (V = constant) permit us to deduce a value of ≈ 0.3. This corresponds well to the expression formerly given by THOMAS (3) who, predicting the initial air velocity to prevent smoke backflow in corridors, has found a correlation with the heat release to the n'th power, where n is 1/3. Then the dependence of non-dimensional reverse layer length on heat release and ventilation speed parameters, is presented in figure 4. The correlation is satisfactory in the range tested. Nevertheless, as the rate of heat release decreases it does not hold (some curvature) since the ventilation can avoid backflow shortly before the extinction of fire.

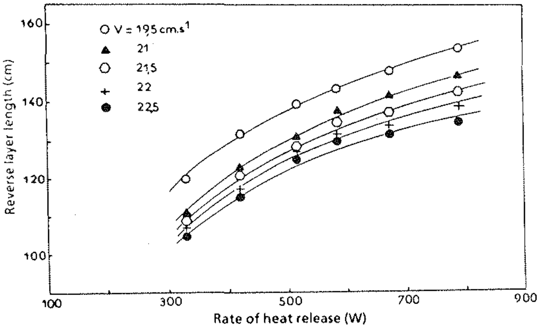
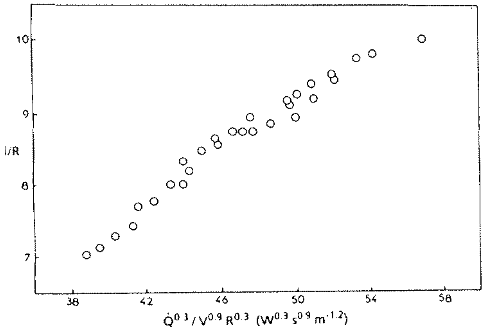


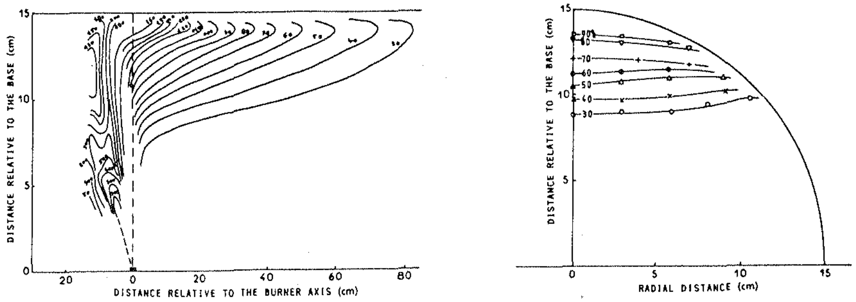
FIGURE 3 Evolution of reverse layer length as a function of the rate of heat release, for different ventilation speeds.

However, one interesting result from this approximate but very simple scaling law is that it can be used to compare behaviour in situations which are similar. For example, according to it, a fire of 50MW in a tunnel with a height of 4.7 m (height of Paris Metro tunnels) and where the ventilation speed is 2 ms^{-1}, could give rise to a reverse layer of about 55 m long. The simple treatment proposed here may have predictive utility to some real situations but confirmation would necessitate some full scale experimental data.

FIGURE 4 Dependence of reverse layer length on heat release and ventilation speed parameters.



For what concerns the temperatures, profiles measured in the median plane reveal a good stratification of the reverse layer. Figure 5a shows



a)

b)

FIGURE 5 Typical temperature profiles (Rate of heat release 710 W, ventilation speed 22 cm s^{-1}). a) Isotherms distribution along the median plane of the tunnel - b) Isotherms distribution along a cross section of the tunnel.

the isothermal field obtained for a source output power of 710 W and a ventilation speed of 22 cms^{-1}. Above the zone affected by the plume, the isotherms look like lines slightly inclined towards the source. It should be noted that it is difficult to draw isothermal curves close to the flame, due to the important turbulence generated in that area and the fluctuations induced in the measurements. Figure 5b reported the transversal evolution of the temperature. The different isotherms were plotted over a tunnel section located 30 cm from the source. They appeared to pile up horizontally, parallel to the floor, without being influenced by the geometry of the section. On a practical view-point, one notes that the smoke occupies, at a maximum, only approximately half the height of the tunnel, as the source is approached. This layer does not, therefore, seems very harmful for the fire brigade unless there is a loss of buoyancy. In the tunnels, furthermore, the cable paths and lighting points are fixed along the walls, at different levels between 2.2 and 2.8 m from the floor. Knowing that the maximum height under the ceiling is 4.7 m, the simulated position for the cables in the scale model can be estimated as being between 7 and 9 cm from the base. The temperature profiles obtained for the different experimental conditions show us that, in all cases, this height interval is located below or next the interface between the fresh air and smoke. When we move further away from the plume, the simulated positioning of the cables and lighting is then never subjected to noticeable thermal affect. The use of a ventilation system, even a weak one, coupled with the air entrainment due to the fire source, ensures a fresh air circulation at a sufficient height to secure cables and lighting systems from damage.

SMOKE MOVEMENT IN A TUNNEL-STATION CONFIGURATION UNDER THE EFFECT OF VENTILATION

This second part describes a series of experiments, of essentially qualitative nature, aim of which is to show the principle characteristics of the smoke flows (entrainment, stratification, recirculation) generated by a fire source developing in a metro tunnel near a station. The configuration of the station used, to carry out this study on a scale model, is that of the stations built in recent years by the RATP in the railway network.

1) Description of the scale model

The scale model was made from polymethylmethacrylate (PMMA or more commonly plexiglass), a transparent material permitting the use of investigative techniques involving lasers, previously described. It is a reproduction of a real station on a scale of 1/30. A sketch of it is reproduced in figure 6. This type of station, parallelepiped in form, includes a mezzanine covering part of the tracks and platforms. This mezzanine is connected to the surface level and an opening, simulating its connection with outside, has been made. The two openings, representing access to the stairs, connecting the platforms to the mezzanine, have also been simulated. The scale model is linked, at both ends, to the two semi-cylindrical shells of borosilicate glass simulating the tunnel and used in the first part of the study. Similarly, the heat source and the device which generates air flow, are those described above.

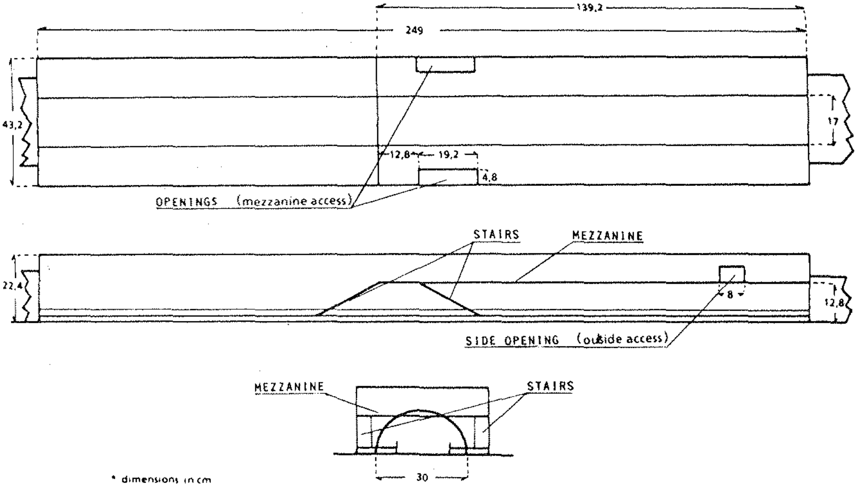


FIGURE 6 Schematic of the tunnel-station scale model.

Two types of layout were studied ; the source in the tunnel near to the station, and on one or other side to the mezzanine.

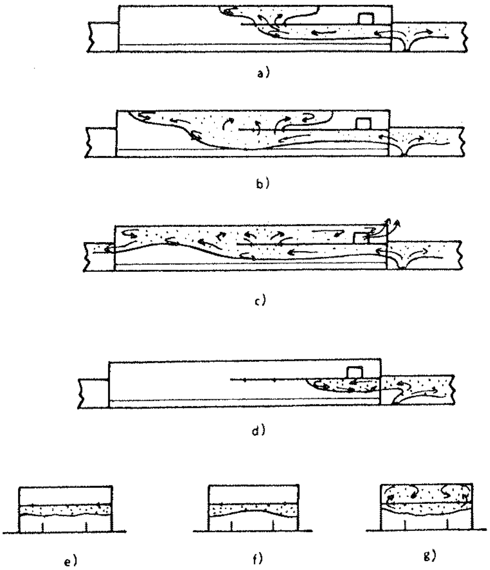
2) Source placed on the same side as the mezzanine

The investigation was carried out for a power source of 1000 W, firstly with a laser sheet in a median plane of the tunnel and the station. If no ventilation speed is applied, the scenario observed is that described by sketches a, b and c of figure 7. The plume impinges on the ceiling of the tunnel and develops into stratified flows simultaneously in two opposite directions, while the fresh air, moving in the opposite direction, is entrained into the lower part in order to supply the source. The smoke layer penetrates the station and spreads under the ceiling of the mezzanine, the stratification of the flow being fairly well preserved. Once it reaches the two openings giving access to the mezzanine by the stairs, the smoke sweeps into them and rises toward the ceiling of the sation, flowing in both directions. Then, the end of the mezzanine is reached and the smoke can continue to spread under the station ceiling and accumulate beneath it. Gradually, the flow joins the flow coming from the openings of the stairs, the layer reaches the whole of the ceiling of the mezzanine and the station, and thickens until it flows into the tunnel, located opposite the mezzanine. Some of the smoke also escapes from the opening at the side of the mezzanine. Gradually, a practically steady state is established and it is possible to conclude that the part of the station which is not covered by the mezzanine is naturally the least smoke-filled. There subsists above the platforms, a high stream of fresh air which might be profitably used for safety. If a ventilation speed is gradually imposed, the scenario is the same as previously, but with a movement of the smoke towards the station and a progressively slower accumulation within it. When the speed is increased, the development of the smoke layer can be blocked beneath the floor of the mezzanine (sketch d of figure 7). If the speed is again increased, all penetration of smoke in the station can be avoided. Thus, according to the ventilation conditions, the smoke can be stopped before it reaches the station, or can almost completely fill it, or can go even further, reaching the opposite part of the tunnel.Finally, if the ventilation is operated only after the station has become filled with smoke, we note that it empties only slowly, even for the mezzanine part. This occurs because the side opening causes an air draft, but some dead zones subsist near corners of the structure, where pockets of smoke are subjected to few of the ventilation effects.

Afterwards, the laser sheet was positioned transversally at increasing distances from the tunnel-station junction. Near this junction, we observe that the smoke layer under the mezzanine ceiling is dense and quite uniformly spread along the broad side of the station. It is very thick and only leaves a thin top layer of fresh air, moving against the current, above the platforms. However, there is almost no smoke discernible above the mezzanine. Indeed, at this short distance from the station extremity, it has not reached the side opening through which it could escape (sketch e of figure 7). A laser sheet, in the middle of the mezzanine, shows a smoke layer a little less thick than previoulsly, but which is not so flat. The smoke layer has a tendency to become thicker near the side walls of the station. This is to be attributed to the preferred direction of the smoke which is attracted by the openings of the stairs (sketch f of figure 7).If the sheet cuts through the middle of the stairs openings, it is possible to observe very clearly the ascending movement through these openings. The layer under the floor is thicker at the centre and the smoke enters the two openings in large eddy structures, which are of opposite direction of rotation (sketch g of figure 7).

3) Source placed opposite the mezzanine

The investigation was carried out, as previously, for a source power of 1000 W and with a laser sheet in a median plane of tunnel and station. Without ventilation, the scenario is that described in sketch a of figure


a)

b)

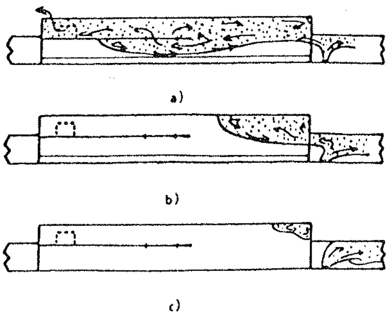
c)

d)

e) f) g)

FIGURE 7 Filling of station with smoke. Source placed on the same side as the mezzanine.

8. The smoke plume develops in stratified layers along the length of the tunnel in both directions. The layer then penetrates the station espousing discontinuity of level and spreading underneath the ceiling. The mezzanine is gradually filled up. The layer becomes deeper until it reaches the mezzanine level and the smoke begins to flow underneath it. Progressively, an almost steady state situation establishes, the smoke escaping through the side opening of the mezzanine. It can be observed that the smoke also enters the stairs openings and that the reverse layer under the mezzanine stabilises, without reaching the opposite tunnel. This last observation is interesting as it shows that a large part of the platforms under the mezzanine can remain sheltered from the smoke propagation. If an increasing current of air is imposed, the smoke only penetrates a very little into the station, following the levels discontinuity (sketch b of figure 8). This constitutes a privileged zone for the formation of recirculating pockets upon which the ventilation has little effect (sketch c of figure 8). This shows the necessity of a rapide smoke extraction to prevent smoke reaching sheltered locations where ventilation is inefficient : recirculation zones, back of obstacles, etc.


a)

b)

c)

FIGURE 8 Filling of station with smoke. Source placed opposite tne mezzanine.

CONCLUSION

The prospect of this work was to show up the main characteristics of fire-induced smoke movement in Paris metro lines and stations. To design experiments for this purpose, scale models were built and adapted to use the recent laser investigation techniques.

Experiments have been performed to offer an approach of the phenomenon of reverse stratified flow of smoke in tunnel and especially to correlate the two main parameters : the effects of ventilation speed and rate of heat release on the length of the reverse layer. The results of these small scale tests have been scaled up using satisfactory modelling procedure. However, it would be very useful to develop also a more theoretical analysis and a mathematical model. Such work is in progress.

The smoke back flow phenomenon may have disastrous consequences for fire fighting activities. The present study allowed us to gain some understanding of the phenomenon in metro tunnels and to draw some informations to prevent propagation. The length of the reserve layer appears to be very sensitive to the ventilation speed. Knowing the dimensions of the tunnels in the Paris metro and the ventilation speeds of comfort used ($\approx$ 1,5 $m.s^{-1}$), one must expect some smoke backflow in the event of important accidental fires. In the absence of forced ventilation, the residual air currents (between 0.2 and 0.4.ms^{-1} measured in-situ) would naturally be too small to counter reverse layers. Nevertheless, it is noticeable that the thickness of the smoke is usually sufficiently weak to preserve, near the floor, a clear and fresh air layer for people. Yet, the potential thermal effect of the hot combustion gases must not be ignored, especially beneath the ceiling where damages are to fear.

It has been also the purpose here to describe and illustrate the propagation of smoke spreading of a fire area in a tunnel and affecting a station. In determining how the smoke affects volumes and escape routes, one can better localise places and ways of safety.

ACKNOWLEDGEMENTS

The authors are grateful to Pr. A.C. FERNANDEZ-PELLO and Dr. C. DUNSKY, Department of Mechanical Engineering, University of California, Berkeley, U.S.A., for their interest in this work.

REFERENCES

1. Eisner, M.S. and Smith, P.B., "Convection Effects from Underground Fires : The Backing of Smoke Against the Ventilation", Safety in Mines Research Establishment, Research Report N°96, 1954.

2. Thomas, P.H., "The Movement of Buoyant Fluid Against a stream and the Venting of Underground Fires",Fire Research Note 351/1958, Fire Research Station, Borehamwood, Herts, England, 1958.

3. Thomas, P.H., "The Movement of Smoke in Horizontal Passages Against an Air Flow", Fire Research Note 723/1968, Fire Research Station, Borehamwood, Herts, England, 1968.

4. De Ris, J., "Duct Fires", Combustion Science and Technology, Vol.2, 239-258, 1970.

5. Alpert, R.A., "Turbulence Ceiling - Jet Induced by Large-Scale Fires", Combustion Science and Technology, Vol.11, 197-206, 1975.

6. Hwang, C.C., Chaiken, R. F.,Singer, J.M., and Chi, D. N. H., "Reverse stratified Flow in Duct Fires : A Two-dimensional Approach", Sixteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, p. 1385-1395, 1977.

7. Lee, C. K., Hwang, C. C., Singer, J. M. and Chaiken, R. F., The Second International Mine Ventilation Congress, 1979, p. 448.

8. Newman, J. S., "Experimental Evolution of Fire-Induced Stratification", Combustion and Flame, 57, 33-39, 1984.

9. Kumar , S. and Cox, G., 5th International Symposium on the Aerodynamics and Ventilation of Vehicle Tunnels, Lille, France, Mai 1985.

10. Hwang, C.C. and Wargo, J. D., "Experimental Study of Termally Generated Reverse Stratified Layers in a Fire-Tunnel", Combustion and Flame, 66, 171-180, 1986.