FIRE RISK IN TUNNEL
AUTOMATION OF THE VENTILATION CONTROL
APPLICATION AT THE MONT BLANC TUNNEL

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ABSTRACT

In 1999, the working group n°6 " Fire and Smoke Control " of the PIARC Committee on Road Tunnels (C5) produced a document entitled " Fire and smoke control in road tunnels ". The recommendations on the ventilation control mention an evacuation phase followed by a fire-fighting phase.

During the refurbishment of the Mont Blanc tunnel, these recommendations are at the base of the regulation rules used for controlling the ventilation system in the case of a fire.

For the evacuation phase, the bidirectional character of the traffic imposes to control the conditions of development of the natural stratification of the hot smoke. This objective is achieved by associating the operation of jet fans with the activation of a capacity of extraction centred on the fire, as soon as the operator validates the location of fire.

This system, entirely automatic, was tested during full-scale tests in January 2002. The results are exceptional since, during the most powerful fires (8 MW), the maximum extension of the smoke (perfectly stratified) was 300 m. These tests played an essential role in the decision of re-opening the tunnel.

The publication summarily describes the Mont Blanc tunnel and its ventilation system. It presents the scientific bases of the development of the stratification. It gives finally a description of the full-scale tests and synthesises interpretations of the mechanisms that were observed on this occasion.

KEY WORDS

TUNNEL / FIRE / VENTILATION / AUTOMATION / STRATIFICATION

1 THE MONT BLANC TUNNEL PRESENTATION

1.1 The conclusions drawn from the catastrophic fire of march 24, 1999

The Mont Blanc tunnel is a 11.6 km long tunnel. It links France and Italy between the Chamonix and Courmayeur valleys. The vehicle traffic is bi-directional, composed of a significant part of HGV.

On march 24, 1999, a HGV fire in the Mont Blanc tunnel caused the death of 39 people, as well as great destruction. The fire propagated to other vehicles. It lasted more than two days.

The madia attention focused on this event because the Mont Blanc tunnel is a major road communication between France and Italy and because its seriousness highlights particular processes of dangerous atmosphere transfers. These processes were observed in the fires that occurred later in the Tauern tunnel in Austria and in the Gotthard tunnel in Switzerland.

These events have shown that a fire occurring on a HGV, involving goods not classified as a dangerous may cause considerable heat and toxic release rates.

Additionally, the confinement of the internal volume of the tunnel helps the propagation of the opacity and toxic conditions over significant distances, without reducing their dangerousness.
Finally, these events have highlighted the fact that an inappropriate operation of the ventilation system increases the consequences of the fire, especially, during the first minutes of the fire.

1.2 The tunnel renovation

As a consequence of this catastrophic fire, it appeared that the refurbishment works had to include a deep renovation of the safety systems, and particularly of the ventilation system.
The tunnel companies ATMB (France) and SITMB (Italy) entrusted the association SCETAUROUTE-SPEA with the renovations studies and works. An international Safety Committee was in charge of providing the specific recommendations and supervised the renovation works.
The most complex phases of the works required more than one thousand people in the tunnel. The works went on two years. The tunnel re-opening to the traffic happened in March 2002.
A European Association for developing commercial interests (Mont Blanc Tunnel GEIE) performs the operation of the renovated tunnel. This association was involved in the renovation studies and works.

2 THE RENOVATED VENTILATION SYSTEM

2.1 The recommendations and some practical consequences

The Safety Committee published recommendations based on the French Circulaire Ministérielle 2000-63.
New dispositions are mentioned by this text:
- The creation of pressurised shelters each 300 m;
- The creation of a pressurised evacuation route, connected to the shelters;
- The increase of the smoke extraction capacity;
- The installation of remote controlled dampers connecting the tunnel with the extraction duct, each 100 m. Existing similar devices were located each 300 m.

Actually, integrating these recommendations led to innovations because it was impossible to increase the existing structure while the ventilation capacities had to increase (Guigas et al., 2001).

2.2 The fresh ventilation system

This system is composed of eight specific ducts connected to as many centrifugal fans (4 at the French portal and 4 at the Italian portal). Each duct includes a transit part exiting in a diffusion part.
In order to take the new pollution threshold values into account, the capacity of each fan is increased to 83 m³/s. The former capacity was 75 m³/s.
At the same time, this system is also used in order to provide fresh air and pressurisation to the shelters during a fire. It is also used as an escape route aiming at evacuating the people out of the tunnel. To satisfy these new functions, it is necessary to open doors between the ducts, in the safety ventilation configuration. This results in a significant imbalance of the pressures and the flow rates between the ducts. The main risk resulting from this imbalance if the excessive pressure loss at the end of a duct where a shelter may be found. These effects were studied and the ventilation levels were adapted to these constraints.

These studies have also highlighted that the efforts that the people have to produce on the doors located between adjacent ducts remain acceptable, especially in the fire ventilation configuration.

2.3 The extraction duct

In the initial configuration, the French and Italian extraction ducts were not connected at the centre of the tunnel. Each duct used to be depressurised by centrifugal fans located at each portal.
The Safety Committee has recommended connecting the two ducts at the centre of the tunnel so that the fans located at one portal can provide assistance to the opposite ones in the case of a failure. The initial extraction capacity used to be about 70 m³/s at each portal. The global effective extraction capacity is increased to 150 m³/s.
The activation of the global capacity at the two portals should normally lead to this result with a significant increase of the fan capacity. Actually, preliminary measurements performed in the ducts have pointed out important leakage between the extraction duct and the tunnel on one hand and the extractions duct and the fresh air ducts on the other hand. The renovation works had to reduce this leakage, but it was clear that they could not be totally reduced.
In order to take this situation into account, it was decided to install four intermediate fans along the extraction duct. They aim at reducing the variation of the pressure. Thus, the leakage is also reduced, resulting in a global effectiveness of the extraction installation.
The extraction dampers are located each 100 m. They are installed in a small duct connecting the tunnel crown to the extraction duct located under the pavement. These dampers are remote controlled. A few of them are opened in the fire area in order to focus the extraction capacity in this zone.

2.4 The tunnel

The Mont Blanc tunnel is subject to important natural pressure differences. Measurements performed in the 60ies have shown that they can reach 600 Pa in one direction or the other. The induced natural longitudinal velocity is then 4 to 5 m/s.
This effect happened during the catastrophic fire. It deeply influenced the recommendations of the Safety Committee.
Since the control of the longitudinal velocity is a major stake of the renovated ventilation system, the tunnel is equipped with 76 jet fans. The unit thrust is 600 N. They are located under the vault of the tunnel.
Activating a jet fan modifies the internal pressure of the tunnel. At the end of the fresh air ducts, the residual pressure level may be of the same magnitude, resulting in the inversion of the ventilation direction through some fresh air louvers. The risk is to promote the penetration of smoke in the fresh air ducts. This effect must be avoided because the fresh air ducts are used for the evacuation of the people. As a consequence, the jet fans are installed in the tunnel far form the fresh air ducts ends.

3 THE PRINCIPLE OF THE AUTOMATION OF THE VENTILATION SYSTEM

3.1 The recommendations

The recommendations imposed by the Safety Committee are the main reference of the renovation studies.
The safety stakes are important. As a consequence, the PIARC 1999 recommendations are also widely used, especially in the conception of the automation of the ventilation system.

This reference mentions two phases to control during a fire:

- ➢ The evacuation phase: During this phase, the people must find acceptable conditions in order to join the shelters. Since the Mont Blanc tunnel is a bi-directional traffic tunnel, the people may be trapped on both sides of the fire. The PIARC recommendation is the control of the ventilation so that the natural stratification of the hot smoke may develop;
- ➢ The fire fighting phase: This phase must allow the fire brigade to join the fire area and fight the fire in acceptable visibility conditions. The recommendation consists in blowing the smoke on one side of the fire.

In a practical point of view, in order to let the stratification developing, it is necessary to maintain a longitudinal velocity as close to 0 m/s as possible in the fire area. At the opposite, in order to blow the smoke on one side of the fire, it is necessary to control a longitudinal velocity greater than a threshold called “critical velocity”. This value is about 2 m/s for small fires (several MW) and about 4 m/s for great fires (several tens of MW).

3.2 The scientific bases

The study of the critical velocity was the object of numerous research works. Even if all the author do not fully agree, the formulation proposed by Kennedy provides a satisfactory synthesis of the various findings (Kennedy, 1996). The mechanical means aiming at controlling this result inside the tunnel are correctly estimated with the help of numerical simulations.

At the opposite, the stratification of the combustion products in a tunnel has been the object of very few studies.

Controlling a low longitudinal velocity in the vicinity of the fire is recognised as a simple and reliable rule to let the stratification developing. Actually, this should not hide a very complex reality.

The principle of the control of the stratification conditions adopted in the Mont Blanc tunnel was the subject of a public presentation in 1999 (Casalé, 1999). This principle is based on various research results aiming at describing the characteristics of the backlayering. This is the hot smoke layer that develops in the opposite direction of the general longitudinal velocity, as soon as the longitudinal velocity remains lower than the critical velocity (Figure 1).

Some simulations involving the reduced scale model in the Valenciennes University (France) have highlighted remarkable singularities developing in the longitudinal velocity profile, in the backlayering zone» (Mégret & Vauquelin, 2000, Mégret, 1999). These singularities, combined with an important vertical gradient reveal a significant stability of the backlayering. At the opposite, these characteristics do not appear in the stratified layer that flows away, downstream of the fire. The major reason is probably the fact that this layer is submitted to intensive exchanges, especially in the zone of the fire drag effects, resulting of the turbulence developing there (Figure 1).

At the same time, numerical simulations performed in the Marseilles University (France) about the representation of the stratification have shown that the turbulence model has to include additional terms aiming at integrating the characteristics of the flows developing in the backlayering (Cordier, 2001, Auguin et al., 2003). The analysis of the signification of these terms led to the same conclusions as those drawn in the Valenciennes University.

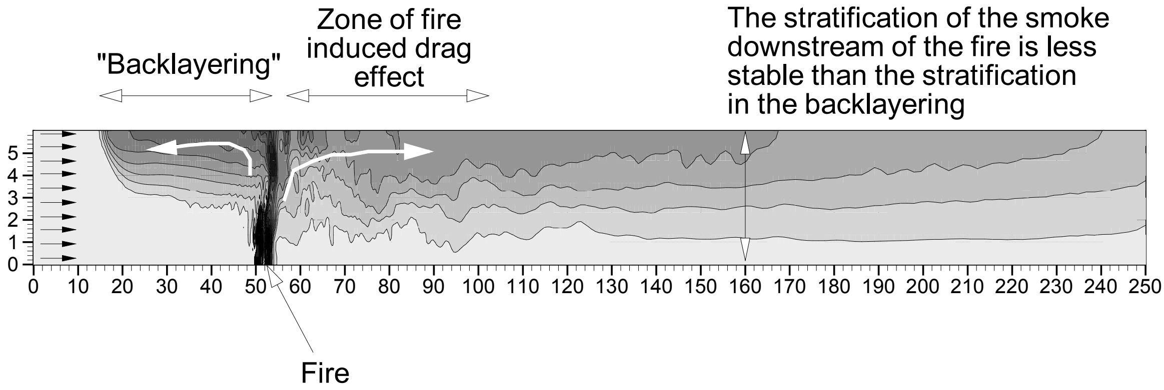

Figure 1 – Numerical simulation of a 1.5 MW fire with a 1 m/s longitudinal velocity. Opacity field after 6 min

Since it cannot be admitted that a stratified layer propagates along the tunnel in an uncontrolled manner, it appeared necessary to look for a method to stop this development. Here also, the longitudinal velocity appears to play a major role. The first results of the research works engaged on the topic (confinement velocity) point out a relationship quite similar to the critical velocity (Casalé & Biollay, 2001).

3.3 Application to the Mont Blanc tunnel

The practical conclusion of the previous findings is that, in order to preserve the visibility conditions during the evacuation phase, it is necessary to develop a stratification which characteristics are similar to those of the backlayering. Since the direction of the longitudinal velocity determines these characteristics, it appears that the ventilation system should induce a converging motion of the air in the direction of the fire. Thus, the stratified layers develop on both sides of the fire in the opposite direction of the local fresh air velocity (Casalé, 1999).

This converging motion is the result of the activation of the extraction capacity and the focusing of this capacity in the fire area. This control does not necessarily result in a symmetrical converging motion.

The symmetry is controlled by the appropriate activation of the jet fans in the tunnel. Since the activation of the jet fans produces a high turbulence level, the stratification cannot be maintained. This is the reason why the jet fans located inside a zone centred on the fire are kept shut (exclusion zone).

The activation of the jet fans is part of a complex regulation loop. The longitudinal velocity is measured with the help of 20 anemometers located along the tunnel. The information provided by the sensors located inside the exclusion zone is not taken into consideration, because it is suspected to be deeply influenced by the local motions induced by the fire.

The regulation loop is installed in the computed located in the control centre. The operator role is limited at the manual validation of the fire location and the activation of the first ventilation phase.

4 THE FIRE TESTS

4.1 The tests conception

The full-scale fire tests appeared as a fundamental requirement for the tunnel re-opening to the traffic. The Safety Committee has asked for fire tests involving significant heat release rates. The chosen value was 8.4 MW.

Preliminary fire tests were decided by the tunnel companies, on the basis of SCETAUROUTE advises. They involve lower heat release rates, 1.4 MW. These tests aim at preparing the Safety Committee tests and at characterising the mechanisms resulting of the interaction of the fire with the motions induced by the ventilation control. The chosen procedures allow the confirmation of the scientific information at the origin of the ventilation control concept.
The full-scale fire tests conclude a series of other tests involving the various ventilation systems.

4.2 The fire source

The fire is located at 8780 m from the French portal, i. e. approximately at the centre of the Italian half tunnel.
The fires involve gasoline pools of 1.2 m diameter. The unit heat release rate is 1.4 MW (about one passenger car). One tub is used for the low heat release rate fires. Six of them are located over ten meters in order to simulate the 8.4 MW fire (about one van fire).

Figure 2 – View of a 1.4 MW fire, at the end of the transient ventilation phase. The stratification and the longitudinal confinement of the smoke are controlled

4.3 The measurement means

About 120 sensors are positioned according to a 3D grid in the fire area. These are mainly thermocouples. Some anemometers are positioned on vertical poles in order to provide the evolution of the velocity profile.
The sensors are connected to data loggers. The information is recorded each 3 s.

4.4 The scenarios

The tests have been performed in January 2002:
- On January 19th: Two tests involving 1.4 MW fires;
- On January 30th: Two tests involving 8.4 MW fires;

The scenarios are reproduced according to the same sequence. Each of the tests is performed twice in order to compare the performances of the automatic system with those of the operator.
During the first test, the control of the ventilation procedure was performed manually. The engineer in charge of the automatism integration replaced the operator. The second test

was performed several hours later, with the fully automatic control of the ventilation system. The scenario is performed as follows:
At t = 0min: Fire ignition. The longitudinal velocity s about 4 m/s in the fire area, in the direction of the Italian portal (Figure 3);
At t = 1 min: Pre-alert activation (Jet fans shut down, extraction fans activation, etc.). The pre-alert was activated at t = 0 min during the tests performed on January 19th (1.4 MW fires);
At t = 2 min: Activation of the alert (the dampers located close to the fire are open, the regulation of the longitudinal velocity is activated, etc.).
The fire duration is about 25 min. After the extinction, the ventilation system is modified to a smoke removal configuration, in order to evacuate the residual smoke present in the tunnel.

5 MEASUREMENT ANALYSIS

5.1 The measurement

The measurement analysis is performed with the help of a specific software developed for several years in SCETAUROUTE for the needs of previous fire tests. This tool provides the evolution of the temperature and velocity fields on the basis of the measurement results.
Since the sensors density is important, the evolution of the thermal fields can be related to the longitudinal velocity controlled by the ventilation system, especially in the fire area. The velocity is calculated from the measurements performed on both sides of the fire. The relevant location of the anemometers is between open dampers (Figure 3). The analysis of the velocity signal derived from the measurement shows that this value decreases down to the range – 1 m/s - + 1 m/s in less than 4 min following the activation of the pre-alert phase. This effectiveness is due to the regulation of the longitudinal velocity with the jet fans.
In this context, the thermal field behaviour reveals the stratification of the hot gases mechanisms (Figure 4):

- During the first minutes of the fire, the smoke is transported by the initial flow, towards Italy. The smoke stratification is lost downstream of the fire and a thermal stratification exists (Figure 4, t = 120 s);
- Two minutes later, the smoke remains located on the Italian side of the fire. At that time, the longitudinal velocity is low and the smoke motion toward the fire is initiated as a result of the activation of the extraction (Figure 4, t = 240 s);
- About six minutes after the beginning of the test, the smoke stratification conditions are obtained. The temperature increases slowly at the ceiling, in the fire area. The smoke stratification develops slowly on this basis (Figure 4, t = 360 s).

The comparison of the system performance with the operator one highlights the great effectiveness of the algorithm implemented in the centralised system. The longitudinal velocity control is obtained in twice less time with the use of the automatic system (Figure 5).

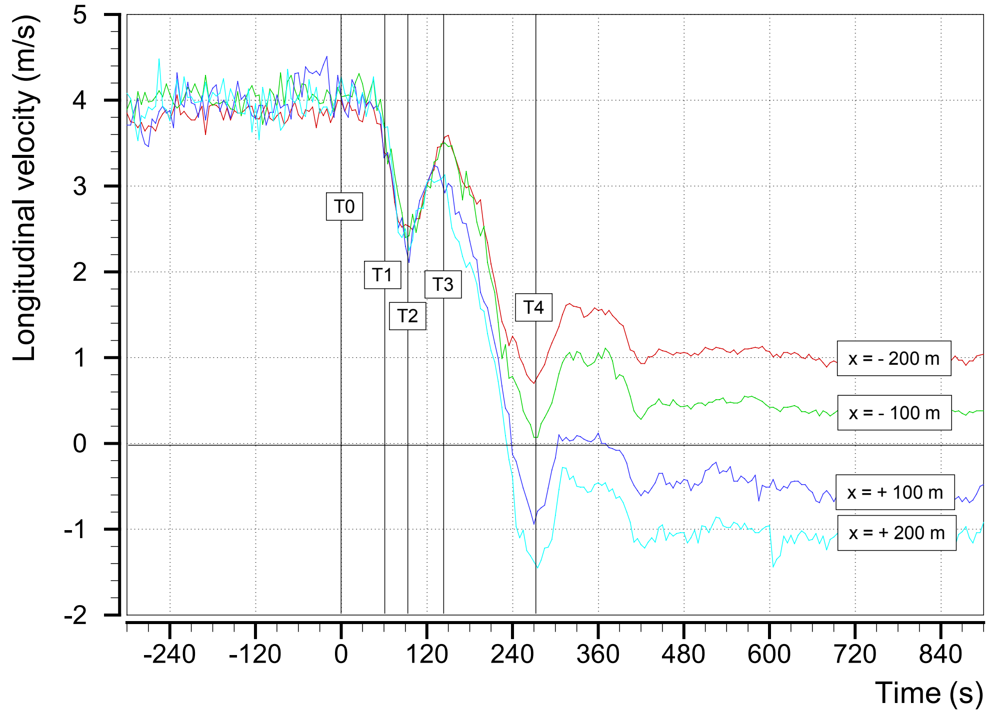

Figure 3 – Mean longitudinal velocity evolution at the measurement sections located on both sides of the fire, calculated from the measurement

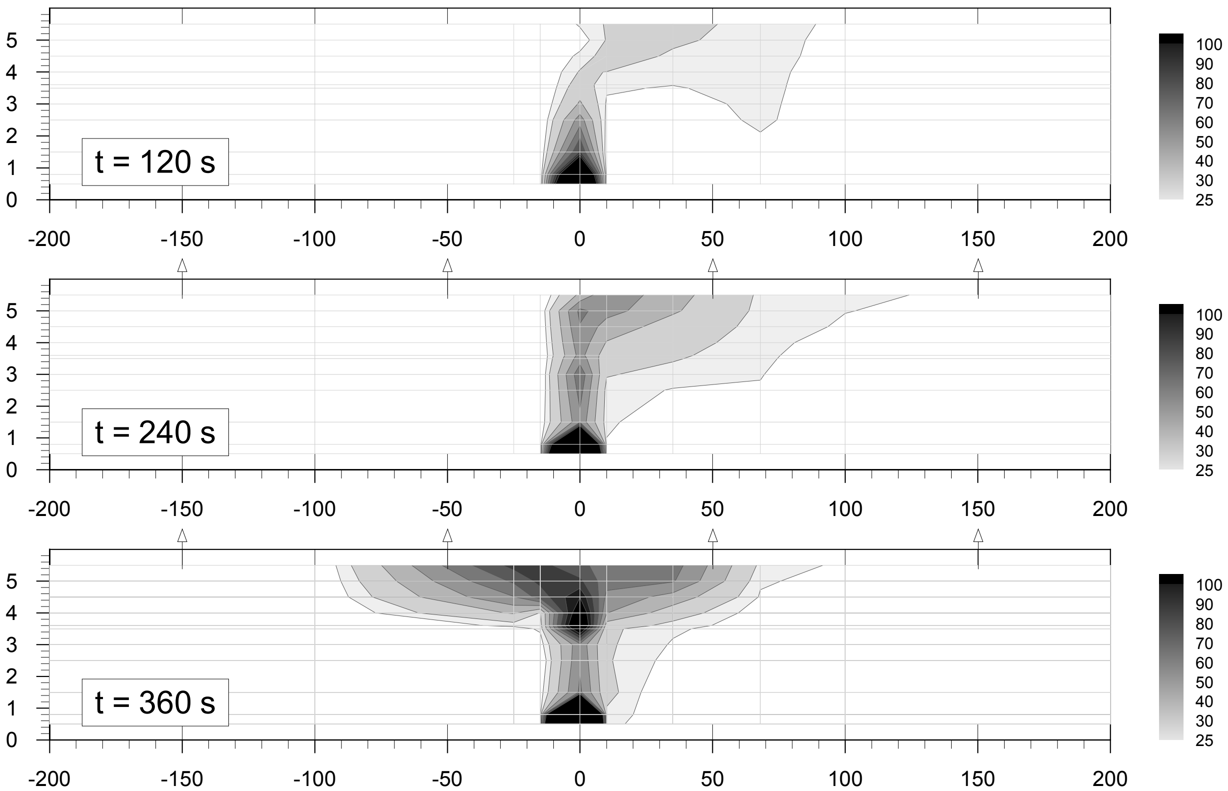

Figure 4 – Thermal field evolution for the 1.4 MW fire, under the automatic ventilation control (the temperature is given in °C). The represented grid gives an idea of the location of the sensors

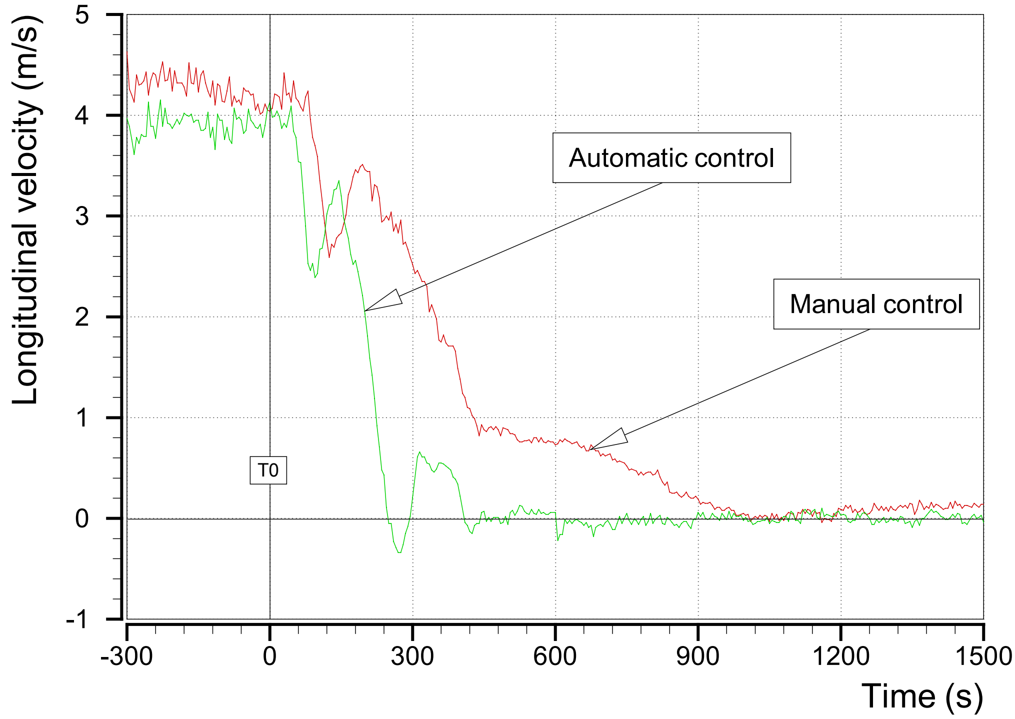

Figure 5 – Comparison of the performance of the automatic system with those of the operator, according to the longitudinal velocity control in the fire area

5.2 The numerical simulations

The fire tests were subject to numerical simulations (CFD). The aim is the comprehension of the phenomena resulting in the stratification development in the fire area. Initially, the smoke affected the complete section.

The simulation of the 1.4 MW fire including the automatic ventilation control provides the following results (Figure 6).

It is shown that the thermal fields are in agreement with the results of the measurement analysis. In other words, the opacity appears to be more invading than the temperature. It affects potentially great distances meanwhile the temperature, subject to the exchanges with the walls or fresh air layers, remains confined close to the fire. The thermal stratification is observed at t = 360 s (Figure 4). The opacity stratification is fully developed significantly later since it appears at about t = 600 s (Figure 6).

The calculation points out also that the opacity found close to the pavement, which requires additional time to be removed, actually corresponds to the smoke initially produced by the fire, transported and destratified by the initial velocity and finally drawn back to the fire area by the controlled velocity resulting from the extraction and the jet fans control. This phenomenon highlights the necessity of efficient and rapid ventilation procedures. It could not be identified by the analysis of the measurements.

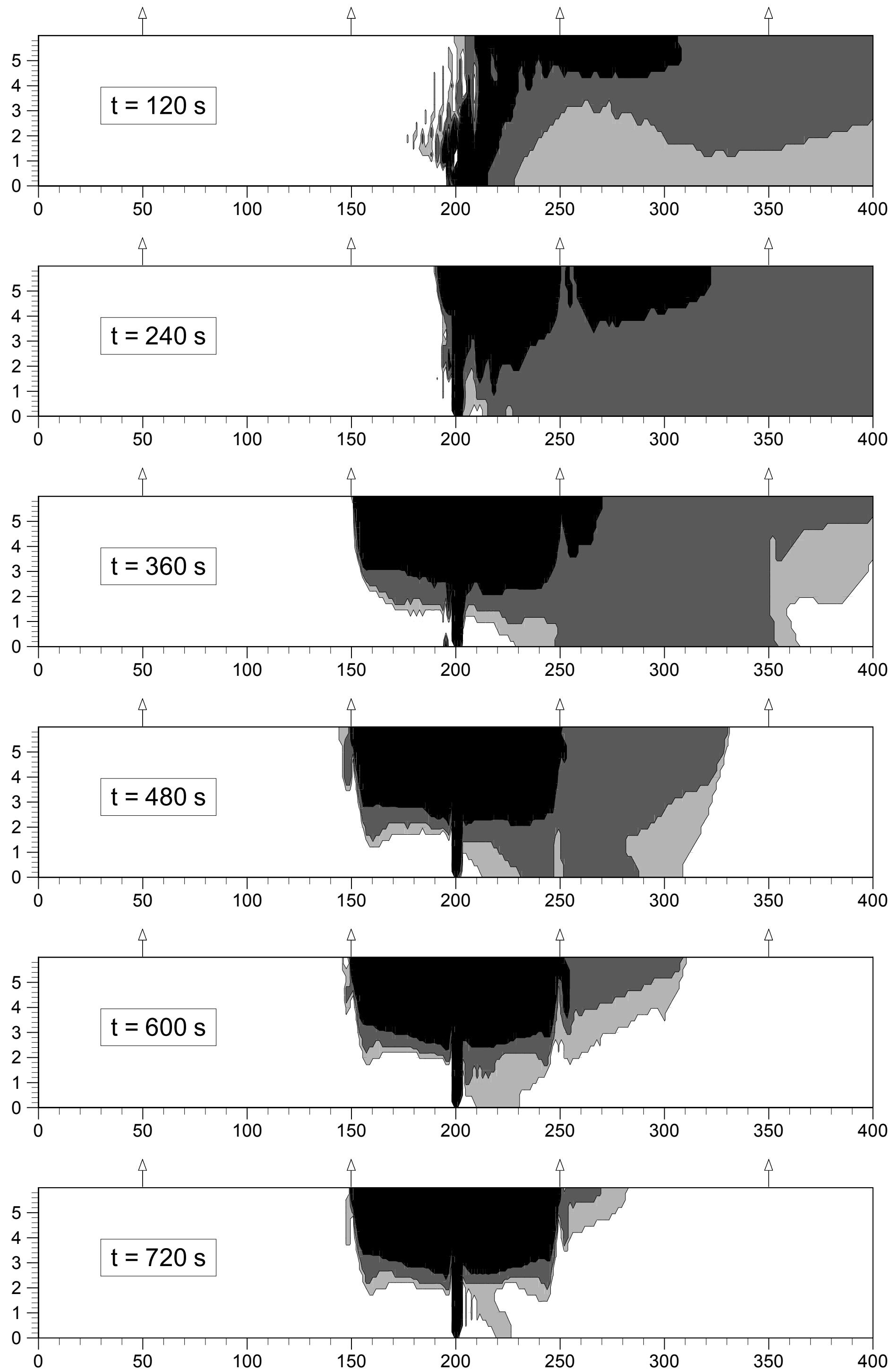

Figure 6 – Calculation of the evolution of the opacity field for the test involving the 1.4 MW fire, with the automatic control of the ventilation

6 FINDINGS AND CONCLUSIONS

The integration of the automatic procedures in the central system of the Mont Blanc tunnel is an important innovation related to the safety. It aims at performing the operation of a complex ventilation system, including the effectiveness and the rapidity. This operation aims at providing an active control of the physical conditions of the evacuation of the people in the tunnel, in the case of a fire. The objective is the control of the conditions allowing the natural stratification of the hot smoke to develop.

The tests performed at the end of the works, preliminary to the opening of the tunnel to the traffic, have shown that the objectives are matched by the ventilation control procedures. They also highlight the effectiveness of the automatic systems, that requires twice less time to control the longitudinal velocity objective than a trained operator. In real fire conditions, it is admitted, and shown that any operator may commit mistakes in the application of the procedures.
The integration of the automatic procedures in the central control system of the Mont Blanc tunnel relates to marginal costs in the renovation works. Most of the costs are actually due to the application of the recommendations.
The automation of the ventilation system, aiming at controlling the safety conditions in the case of a fire, used to appear as utopia several years ago. The technical success of the Mont Blanc tunnel is now a fundamental reference for new tunnels or renovation works.

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