SMOKE STRATIFICATION STABILITY:
RESULTS OF EXPERIMENTS

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ABSTRACT
This paper presents an experimental campaign achieved on a 1/3 scale model tunnel. Its aims at study the influence of the heat release rate, the introduction of an injector and the presence of vehicles on the smoke layer characteristics.

Firstly, two smoke layer parameters are defined to characterise the backlayering: the smoke layer length and the dimensionless thickness of the smoke layer. Secondly, the experimental results permit to determine the influence of perturbation presence on these parameters.

The analyse of the heat release rate influence shows that the scale model allows to represent correctly the backlayering comportment as in a full scale tunnel. The introduction of a jet induces a diminution of the backlayering length and the impact on the smoke layer thickness depends on the heat release rate and the velocity jet while no destratification is observed. However, the presence of vehicles does not enable to conserve visibility in the gallery, even if a thermal approach is not in accordance to experimental observation.

1. INTRODUCTION
Longitudinal ventilation in road tunnel is usually used in case of unidirectional non-congested traffic. In such case the vehicles located downstream the fire leave normally the tunnel before to be reach by any smoke. In case of congestion, this assumption is not anymore satisfied. The longitudinal approach is not able to ensure safe evacuation conditions.

This case occurs frequently for urban tunnel that are cut and cover. The solution used is to try to obtain the stratification of smoke upstream and downstream the fire. The mechanical ventilation is then used to maintain the longitudinal airflow at a low velocity to provide favourable conditions for stratification. This means that the tunnel jet fans or the tunnel injectors are used to control the physical phenomenon occurring in the tunnel (natural ventilation, chimney effect).

However, the stratification may be disturbed by several local phenomena. The present study aims at analyse the impact of two of them. The first one is the interaction between the smoke layer and an air jet of the ventilation system. The second one is the impact of the presence of vehicles on the stratification. These two causes of stratification perturbation are almost always presents for such case of congested traffic ventilation mode.

The study has been performed using an experimental device. However, this campaign has also been design to provide data for numerical simulation calibration. The present paper is only relating the experimental campaign.
2. EXPERIMENTAL SETUP

The experimental campaign was achieved using the INERIS fire gallery (Boehm et al., 2008): a 50 m long device with a section corresponding to a 1/3 scale tunnel with a maximum cross section of 5.4 m². The experimental setup is schemed on Figure 1. This gallery corresponds to a 150 m long full scale tunnel with a maximum cross section of 48.6 m².

![Figure 1: Scheme of the experimental setup](image)

The gallery needs to be conferred to simulate the backlayering layer founded sometimes during tunnel fires. The smoke is extracted by a fan installed in the chimney. The fresh air could arrive by the other extremity of the tunnel. Therefore, the fire is placed at 10 m of the chimney to create a backlayering: the smoke layer flows in the opposite direction of the fresh air.

Furthermore, the longitudinal velocity needs to be around the critical velocity to allow the backlayering layer formation and avoid the propagation of the smoke out of the tunnel. For this study, the critical velocity is 1.28 m/s for the fire pool of 0.25 m² and 0.95 m/s for the pool fire of 0.2 m² (Kennedy et al., 1996). The longitudinal velocity is fixed around 0.95 m/s.

The smoke duct allows representing a transversal ventilation system but is not used in the present paper.

The Froude scaling is a mean to scale model parameters that would produce a similar flow in the full-scale tunnel. It’s also necessary to scale the model results. Froude scaling enables to correctly model the thermal effect and particularly the backlayering phenomenon (Oka et al., 1995).

The fire is modelled using an heptane pool fire. The use of two different pools (0.25 m² and 0.2 m²) allows simulating two heat release rates. These experiences aim at knowing the influence of this parameter on the smoke layer characteristics. The fire can be characterised by three different heat release rates: the theoretical total heat release rate calculated from the mass consumption of heptane, the total heat release rate computed from the oxygen consumption and the convective heat release rate with volumetric flow rate estimated by integration of the velocity profile measured downstream of the fire.

The difference between the two total release rates is the combustion efficiency. For the pool of 0.25 m², the three heat release rates are respectively: 358 kW, 303 kW and 249 kW. For the pool of 0.2 m², they are respectively: 266 kW, 242 kW and 184 kW. Thus, the combustion efficiency is 85% and the radiative fraction is 30% for the 0.25 m² heptane pool fire. The combustion efficiency is 90% and the radiative fraction is 31% for the 0.2 m² heptane pool fire.
3. SMOKE LAYER PARAMETERS

The smoke layer can be characterised by the repartition of temperature, density and velocity.

In this study, the measures of temperature are made along the backlayering layer; a device with thermocouples moves along the tunnel (Figure 2).

The velocities are measured at two positions on the gallery: 5.5 m and 17 m from the fire.

The repartition of density is not explored as this measure should be difficult to release in this type of experience (heptane fire in a 1/3 scale tunnel).

Two parameters for describing the backlayering are extracted of the temperature and velocity fields: the backlayering length $l_b$ and the layer thickness $\delta_b$.

The temperature repartition measured enables to deduce the backlayering length. The length is deduced of the position where the temperatures are equals on the vertical profile.

It is possible to compute the smoke layer thickness at two places because the temperatures and velocities profiles are required to calculate its. In fact, the smoke layer thickness is calculated using the smoke mass flow conservation (Figure 3).

On the Figure 3, three heights are represented:
- $H$ is the height of the gallery;
- $H_1$ is defined as the point where the velocity is null in the vertical profile;
- $H_2$ is the point at the flow of the smoke flowing on the opposite direction of the fresh air is equal to the flow of the smoke flowing in the same direction of the fresh air.

Thus the backlayering thickness is the difference between the heights $H$ and $H_2$.

4. INFLUENCE OF HEAT RELEASE RATE ON THE SMOKE LAYER PARAMETERS

The length and the thickness of the backlayering depend on the heat release rate.

The smoke layer length increases with the heat release rate: 27 m for the 0.25 m$^2$ pool and 21 m for the 0.2 m$^2$ pool. In fact, the thermal energy is more important in the smoke layer for the highest fire. The equilibrium of strengths is ensured closer to the fire for the case of the 0.2 m$^2$ pool than for the case of the 0.25 m$^2$ pool.
The velocity measure was released at 5.5 m and 17 m of the fire. Thus, the smoke layer thickness is calculated at these two positions for the two heat release rate modelled. The thickness is divided by the height of the tunnel (the length parameter in this study) to create a dimensionless number.

On the Figure 4, the evolution of the dimensionless thickness along the gallery is represented for the two heat release rate.

The thickness decreases with the rising of the distance from the fire for the two heat release rate simulated. Furthermore, the dimensionless thickness increases with the heat release rate. This difference diminishes with the augmentation of the distance from the fire.

These results present limitation as experience are released on a small scale tunnel. The experimental campaign of the Memorial tunnel, achieved on a large scale tunnel, provides the same conclusion for the influence of heat release rate on backlayering characteristic. A higher heat release rate leaves to a thicker and longer backlayering (MTFVTP, 1995).

5. **INFLUENCE OF THE INJECTOR ON THE BACKLAYERING LAYER**

In longitudinally ventilated tunnels, injectors are placed on the tunnel to generate an air flow. This presence induces a gradient on the vertical profile of velocity which should break the smoke layer stratification. This part aims at analysing the influence of this gradient on smoke layer parameters.

5.1. **Experimental representation of the injector**

The velocity profile gradient created by the injector is modelled by a plane jet of 0.6 m of height and 3 m of width. This plane jet is designed to avoid the rotational effect which cause complex coupled physical phenomena. The output velocity of the jet is about 3 m/s. The air fresh flow rate at the entrance is conserved with and without disturbance. In a second case, the height of the plane jet is reduced to 0.3 m with the same flow rate. Thus, the velocity of the jet is about 6 m/s. The backlayering parameters are compared for the cases without jet and with the two different jets.

5.2. **Influence of jet on smoke layer parameters**

The plane jet which modelled the injector creates a gradient on the velocity vertical profile. The longitudinal velocity of the fresh air is more important near the ceiling in the case with jet than in the case with no disturbance. Hence, the smoke layer length is reduced as the strengths equilibrium is insured closer of the fire in the case with jet than in the case without jet.

In fact, the lengths of the backlayering measured on the experience are reported on the table beneath.
<table>
<thead>
<tr>
<th>Backlayering length</th>
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<tr>
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<tr>
<td>Pool of 0,25 m²</td>
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<tr>
<td>No jet</td>
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<tr>
<td>Jet of 3 m/s</td>
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<tr>
<td>Jet of 6 m/s</td>
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The two jets induce a reduction of the backlayering length more important for the 0.2 m² pool than for the 0.25 m² pool.

For the case with disturbance, the thickness evolution along the tunnel is calculated for the pool of 0.25 m². For the 0.2 m² pool, one position of velocity measure is outside of the backlayering and the thickness could not be calculated for this place.

The evolutions of thickness for all the cases are reported on the Figure 5.

For the pool of 0.2 m², the introduction of the two jets has the same effect on the dimensionless thickness of the layer: the diminution of this parameter.

However, for the pool of 0.25 m² the presence of the 3 m/s velocity jet induces an increase of the thickness whereas the 6m/s velocity jet diminishes the smoke layer thickness. This diminution is more important when the distance from the fire increase.

The modification of these parameters due to the presence of a jet enables to analyse the influence of jet on smoke layer characteristics. However, they don’t allow to quantify the stratification and to determine the influence of a jet on its.

6. **INFLUENCE OF THE VEHICLES**

6.1. **Experimental vehicle reproduction**

The experimental device is the one above described for studying the injector influence. Due to the third scale of the experimental device, third scale vehicles were used for studying their impact on the backlayering layer. Considering this, obstacles were built to reproduce scaled vehicles; shape and dimension of these vehicles and a visualisation are given on Figure 6.
Figure 6: Schematic representation of scaled vehicles and photography inside the gallery

Truck on the right lane of the tunnel with a car on the left induces a blockage rate of 53%, this means more than the half of the tunnel section is occupied with vehicles. This represents the case of a small cut and cover 2 lanes and 2 sidewalks.

6.2. Impact of vehicles on air flow velocity

It first appears clearly that vehicles upstream the fire will have a significant influence on the backlayering layer. Such vehicles will generate a restriction and consequently a velocity increase as observed during experiment without fire. Vertical velocity profile with and without vehicles are reproduced on Figure 7.

Figure 7: Vertical velocity profile with and without vehicle

Depending on the restriction factor, the local velocity can become higher than the critical one. This configuration should block the backlayering layer and disturb it. The second phase of the experimental campaign aims to evaluate vehicles impact on the backlayering layer.

6.3. Influence vehicles on smoke layer parameters

Because the velocity rise due to the restriction, the length of the backlayering layer is reduced, the velocity near truck is higher than the critical velocity. The backlayering length was measured around 10 m for the experimental case but this value highly depends on vehicles distribution upstream the fire and mainly the truck location. This first result shows that not only the ventilation governs the backlayering layer but the vehicles distribution upstream the fire too.
The experimental consequence of this layer length reduction is that only one of the two velocity measurement sections is available, the one located 6 m upstream the fire.

The backlayering thickness computed 6 m upstream the fire is 0.29 m value to be compared with the 0.25 m thickness for the reference case without vehicles. The second conclusion that appears is that the layer seems to stay stratified with an increase of its thickness around 15% from the reference case without vehicles. It is however highly important to highlight that this result depend on vehicle distribution upstream the fire and that, this increase should be different, higher or lower, for other blockage configurations.

6.4. Synthesis

The physical analysis of the backlayering layer in case of vehicles blocked upstream the fire shows that, the thickness of this shortened backlayering layer increase. It must be noted that this analysis is mainly based on a physical criterion considering that the layer is stratified and that its height is as defined in section 3. A distinction between this physical analysis and the people security in the lower part of the tunnel has to be made. Considering people safety, it is important to consider not only physical approach but pragmatic one too. Doing this implies to consider the different components of a stratified layer. Smoke effects on human beings can be split into three aspects, two direct effects which are thermal and toxic impact and an indirect one which is visibility reduction. If the visibility diminishes, this will induce some difficulties in the tunnel evacuation but this will have no direct impact on people on the opposite of a temperature or toxic concentration rise.

In the present case, it can be shown that visibility in the lower part of the tunnel decrease, Figure 8.

![Video camera picture for test with vehicles](image)

**Figure 8**: Video camera picture for test with vehicles

7. CONCLUSIONS

This experimental campaign is achieved on a 1/3 scale model tunnel. Consequently, it would present some limitations as the Reynolds and the Richardson numbers cannot be reproduced both. The analyse of the influence of heat release rate on the backlayering shows that a higher heat release rate leads to a longer and thicker backlayering layer as observed in large scale tunnel. The smoke layer thickness is calculated using the smoke mass flow conservation and not using only the temperature profile.
The first experimental configuration aims at determine the impact of a plane jet on the backlayering layer characteristics. The introduction of a jet implies a diminution of the backlayering layer length: this diminution rises if the jet velocity is increased. The second consequence of the jet presence is a diminution of the dimensionless smoke layer thickness for the lower heat release rate. However, for the higher heat release rate, the evolution of this thickness depends on the jet velocity: decrease of the thickness for the lower velocity jet and increase for the higher velocity jet. This influence increases with the distance from the fire as the smoke layer thermal energy diminishes when the layer spreads along the gallery.

Numerical simulations are needed to analyse more precisely the impact of the jet parameters (velocity, distance from the fire…) on the backlayering and to determine a number which permit to define the stratification stability.

The second experimental configuration, with vehicles blocked upstream the fire gives two main information. The first one is that not only the ventilation governs the backlayering layer behaviour but the vehicles have a great influence in terms of length reduction and of thickness increase. The second information mainly concerned the stratification definition. Most authors considered only the temperature profile to define the stratification criteria, considering the difference between the near ceiling temperature and near ground one (Newman 1983, Newman 1984, Cooper 1982 and Chow 2009). In this paper, a new approach is developed to computed the backlayering layer and then evaluate stratification. For both cases, this only considers one physical quantity related to one layer property, which shows some limitations in case of stratification transition regime as in case of vehicle upstream the fire.

8. ACKNOWLEDGEMENT

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9. REFERENCES