MODULAR VENTILATION OF URBAN ROAD TUNNELS USING AIR CURTAINS – PART I: CONCEPT AND BEHAVIOR OF THE CURTAINS

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Lucrarea de faţă prezintă o soluţie originală cu privire la ventilarea tunelelor urbane de lungime medie şi mare folosind perdele de aer. Varianta propusă reprezintă o combinaţie între ventilaţia transversală şi cea mixtă, elementul de noutate fiind izolarea aerodinamică a tronsoanelor tunelelor simultan cu asigurarea unui curent longitudinal direcţionat către avalul tronsoanelor. Prin modularea tunelelor şi prin utilizarea perdelelor de aer transversale se pot izola secţiunile de tunel una faţă de alta şi faţă de exterior. În prima etapă a cercetării a fost studiată stabilitatea perdelelor de aer propuse şi mişcarea aerului în jurul unui obiect paralelipipedic asimilat unui autobuz care se deplasează printr-un modul. În a doua etapă se va lua în consideraţie captarea şi epurarea emisiilor poluante.

This paper presents an original solution concerning the ventilation of urban road tunnels of medium and large lengths by using air curtains. The proposed variant is a combination between transverse and mixed ventilation, the novelty consisting in an aerodynamic isolation of tunnel sections while a longitudinal air flow directed downstream is provided. By modularization of the tunnel and use of transverse air curtains tunnel sections can be isolated from each other and from the outside. In the first part of the research the stability of the proposed air curtains and the air flow around a hexahedral object assimilated to a bus moving along a module were investigated. In the second part the extraction and cleaning of the polluted air is considered.

Keywords: urban road tunnel, pollution, ventilation, air curtains, stability.

1. Introduction

In big cities, the ever increasing number of vehicles is leading to slow moving and even stationary traffic, especially at rush hours. Traffic congestions can be avoided, at least partly, by building urban road tunnels. There are situations, in which such tunnels have hundreds of meters or even kilometers in length. There are different problems associated with long road tunnels, some of them being created by the pollution generated inside the tunnel by vehicle exhausts. On one hand, the air in the tunnel must be properly ventilated to avoid impairing the health of the people traveling through the tunnel. On the other hand, the pollution level in the

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immediate vicinity of tunnel portals or venting towers tends to be higher than in other neighboring areas, because of the polluted air that exits from the tunnel. In order to meet the air quality standards by keeping the pollution level at tunnel portals as low as possible, solutions that prevent polluted air from exiting from the tunnel should be adopted, when designing the ventilation system of the tunnel.

There are three main types of ventilation systems used in road tunnels: natural ventilation, transverse ventilation and longitudinal ventilation. While natural ventilation is suitable for short tunnels, long tunnels require either transverse or longitudinal ventilation. Transverse ventilation systems allow fresh air to be introduced and stale air to be removed uniformly throughout the tunnel [1]. Moreover, Nishiuma *et al.* [2] demonstrated that for transverse ventilation systems a properly chosen imbalance operation of the blowing and exhausting flow rate could prevent portal emission. Komatsu *et al.* [3] proposed a ventilation method consisting of a transverse ventilation system with an extraction shaft, which was proved to be effective against environmental pollution around exit portals of road tunnels. However, Chiu *et al.* [4] suggested that is more cost effective to use longitudinal ventilation systems. Such systems make use of either large fans or longitudinal jet fans in order to induce airflow throughout the tunnel section [1]. To extract polluted air from the tunnel and reduce portal emissions different solutions may be employed, depending on tunnel length and configuration. In some cases exhaust chimneys or shafts are used [5, 6, 7], in other cases additional ventilation tunnels are built for extracting polluted air from certain locations in the tunnel, e.g. from the center of the tunnel [8]. Despite its cost effectiveness, the longitudinal ventilation has certain drawbacks. One drawback is that the concentration of exhausted gases increases towards the portals and/or exhaust shafts. In this way, regions with a high pollution level may appear in the tunnel. Another drawback is that due to the piston effect produced by the moving vehicles, exhausted gases are pushed outside the tunnel through the exit portals. This leads to an increase in the pollution level in the vicinity of the portals. To diminish as much as possible the aforementioned drawbacks, a solution is proposed in this paper, which consists in the creation of tunnel modules by using special barriers. The barriers are air curtains generated by cross-flow fans placed close to the portals and at other locations in the tunnel. By means of these air curtains the air movement can be restrained while allowing the vehicle movement, so that one or more tunnel sections could be aerodynamically isolated from the outside and from each other. The number of isolated sections will depend on the tunnel length. In each section fresh air is introduced close to the upstream curtain. The air containing increasing concentrations of exhaust gases is then pushed towards the downstream curtain by the piston effect created by the moving vehicles and by small fans placed near the ceiling. Close to the downstream curtain the air is sucked out from the tunnel and, after a cleaning process, is released to the atmosphere. The length of each isolated section, i.e. the distance between two curtains, can be chosen depending on the allowed concentration of exhaust gases.

Each air curtain is a free jet created in a cross-section of the tunnel. While the air in the jet moves towards the opposite wall, the jet section will increase and the velocity will decrease, which could reduce the efficiency of the curtain. It should also be considered that the jet will be subjected to perturbations due to air currents and moving vehicles. To improve the efficiency and stability of the air curtains against disturbances created by air currents and moving vehicles, instead of a single curtain a pair of two curtains could be used. The most appropriate solution for creating the pair is to place the two cross flow fans such that one's outlet faces the other's inlet. In this way, the air blown by one fan is sucked by the other. The jet growth and the decrease of the jet velocity are then expected to be smaller and, consequently, the efficiency of the curtain is expected to be higher. Also, the recovery of the curtain after being broken by a moving vehicle is expected to be faster.

Considering now the two curtains configuration, the following questions arise: (i) what should be the distance between each two curtains in a pair, so that these two free jets do not influence and destabilize each other? (ii) to what extent will the curtains be disrupted by moving vehicles and how fast will they recover? (iii) where is the most appropriate place, upstream the curtains, for the intake of the ventilation system's fan?

An approximate answer to the first question can be provided by using results obtained for single plane free jets. Let x denote the coordinate along the symmetry axis of one jet forming a curtain and y the coordinate perpendicular to the symmetry axis. In our problem, the x-axis is required to be a straight line normal to the tunnel direction. A measure for the jet width is the half-value width, i.e. the local distance of the points with half the maximum velocity. The half half-value width of a free jet is [9]

$$y_{0.5v} = 0.11(x - x_0), \quad (1)$$

where x_0 denotes the position of the virtual origin of the flow. For a tunnel width of 6 m, as in our problem, at the middle of the tunnel, i.e. for $x = 3$ m, an estimate of the half half-value width of one curtain is $y_{0.5v} \approx 0.3$ m. It results that the distance between two curtains should be no less than 0.6 m in order to avoid the mixing followed by the destabilization of the two curtains. If it is taken into account that we only estimated the half-width value, the minimum distance should be actually no less than about 1.2 m.

To seek clearer answers to the questions formulated above, a study was prepared and undertaken. Numerical simulations were employed to investigate the three-dimensional, unsteady, turbulent flow within and in the vicinity of two air curtains created in a tunnel. Two distinct cases were considered: one in the absence and the other in the presence of a moving vehicle. The computations were performed with the CFD program FLUENT, which uses the finite volume method. In the following, the problem is formulated for each case in terms of geometry, parameters of curtains, vehicle dimensions and velocity (for the second case only), and numerical algorithms used. Obtained results are then presented and considerations are made with regard to the stability of the curtains and how they are influenced by a moving vehicle.

2. Air curtains in the absence of moving vehicles

A sketch of the computational domain's geometry chosen to study the behavior of two curtains forming a pair and to estimate the required distance between them is presented in figure 1a. In the sketch the geometry of the inlets and outlets is distorted for the sake of clarity. The tunnel width and height are W and H respectively. Upstream and downstream of the curtains there are two tunnel parts of lengths L_1 and L_2 respectively, which will be separated by the two curtains. On the right wall there is the outlet of one of the two cross-flow fans followed, at distance ΔL, by the inlet. On the left wall the arrangement is reversed: the inlet of the second cross-flow fan is followed by the outlet. As already mentioned, the outlet of each fan is facing the inlet of the other fan. The lengths of the inlets and outlets are L_i and L_o respectively. The height of both the outlets and the inlets is equal to the tunnel height H. For the purpose of our simulations the following dimensions were considered: $W = 6$ m, $H = 4.5$ m, $L_i = 0.234$ m, $L_o = 0.084$ m. The lengths L_1 and L_2 were varied between 4 m and 5 m, depending on ΔL. A total number of 6 simulations were performed, for the following values of ΔL: 0.4 m, 0.6 m, 0.8 m, 1.0 m, 1.5 m and 2.0 m. The computational domain was spatially discretized using hexahedral volumes. Boundary layers were used close to the walls. The computational mesh obtained for $\Delta L = 2.0$ m is presented in figure 1b.

The air was considered to be a newtonian, incompressible fluid. For the chosen reference pressure $p_0 = 10^5$ Pa and the chosen reference temperature $\vartheta = 15°C$ (absolute temperature $T = 288.15$ K) the values of air density and dynamic viscosity are $\rho = 1.208$ kg/m^3 and $\eta = 1.8 \cdot 10^{-5}$ Pa·s respectively.

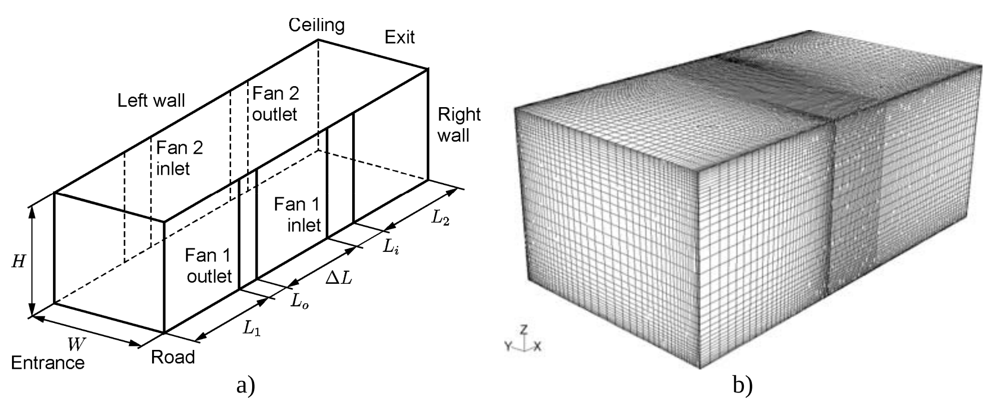


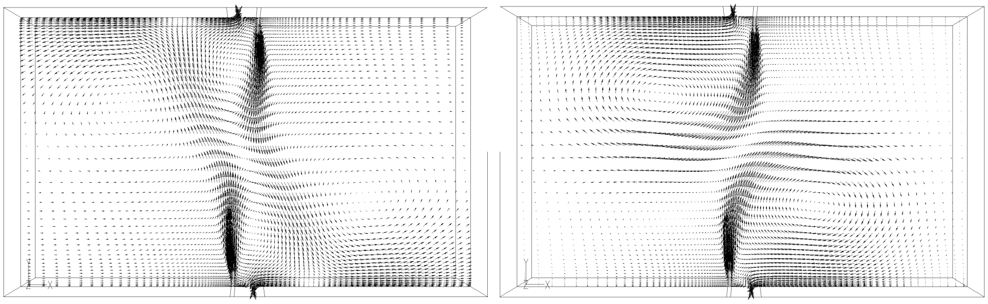
Fig. 1. Computational domain: a) sketch of the geometry, b) spatial discretization for $\Delta L = 2$ m.

The unsteady, incompressible, turbulent flow is described by the continuity equation, the momentum equations and the equations of the turbulence model. When choosing the turbulence model it must be considered that the air curtains are, to a very large extent, free jets, i.e. free shear flows [9]. It must also be considered that the air flow in the tunnel is influenced by the solid walls. An appropriate model for wall-bounded flows and free shear flows, whose predictions are in close agreement with measurements, is the k-ω model [10], where k is the turbulence kinetic energy and ω is the specific dissipation rate. A variant of the k-ω model is the shear-stress transport (SST) k-ω model, which implements a gradual change from the standard k-ω model in the inner region of the boundary layer to a high-Reynolds-number version of the k-ε model in the outer part of the boundary layer. The SST k-ω model has an advantage in terms of performance over both the standard k-ω model and the standard k-ε model and behaves appropriately in both the near-wall and far-field zones [10]. Due to the advantages that it offers in the context of the studied problem, the SST k-ω model was chosen to model turbulence.

The boundary condition at the walls was the usual one of no-slip. At each fan outlet a mass flow rate of 7 kg/s was imposed. The average velocity in the outlet section corresponding to this mass flow rate is about 15.3 m/s. The same mass flow rate was evacuated through each fan inlet. Both at the entrance in the considered tunnel part and at the exit a relative pressure of 0 Pa was imposed. At the initial time the air was considered at rest, i.e. the air velocity in the entire domain was set to zero.

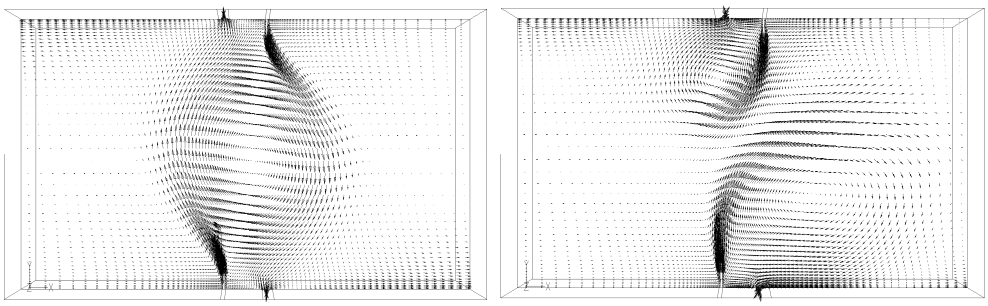
The governing equations were discretized in space using the finite volume method and in time using first-order accurate backward differences. The time integration was implicit. To solve the equations, a segregated solver was chosen. The solution was advanced in time with a time step of $\Delta t = 0.1$ s. For each time step it was considered that the solution converged after the residuals of all governing equations dropped below 10^{-3}.

The results obtained suggest that the time required for the curtains to form is about 20 s. As expected, the behavior of the curtains is strongly influenced by the distance between them as long as this distance is small or relatively small. When the curtains are placed very close to each other two effects appear. On one hand, the curtains come into contact and interact directly because of the growth of the two air jets. On the other hand, because of the depression created close to the fan inlets, the curtains deviate towards the inlets and start flowing one against the other. As a consequence of the interaction, each curtain starts oscillating continuously around the vertical symmetry plane of its outlet. This behavior is depicted by figure 2, which shows velocity vectors plotted for $\Delta L = 0.4$ m, at different time moments, in a horizontal plane situated at 2.25 m above the road (i.e. at tunnel half height). As the distance increases, the mechanism that destabilizes the curtains changes. Because of the increased distance, just the widening of the air jets is no more enough to bring the curtains into contact and the influence of the fan inlets becomes less significant.



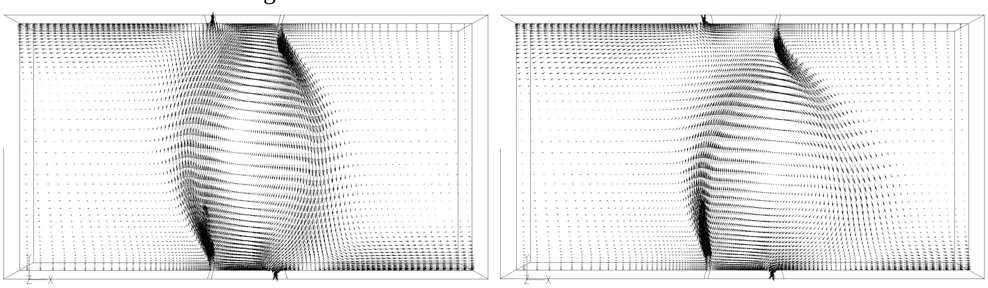
a) $t = 24$ s b) $t = 27$ s

Fig. 2. Behavior of the air curtains for $\Delta L = 0.4$ m.



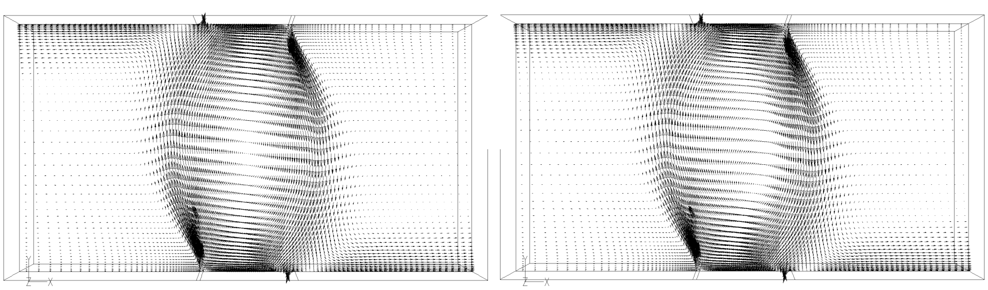
a) $t = 21$ s b) $t = 28$ s

Fig. 3. Behavior of the air curtains for $\Delta L = 0.8$ m.



a) $t = 22$ s b) $t = 33$ s

Fig. 4. Behavior of the air curtains for $\Delta L = 1.5$ m.



a) $t = 20$ s b) $t = 40$ s

Fig. 5. Behavior of the air curtains for $\Delta L = 2.0$ m.

Instead, a vortex, which appears for short periods of time between the curtains, plays a more important role in the behavior of the curtains. As a consequence of the vortex influence, the curtains start to oscillate, first moving off from each other and then intersecting with each other. In the process, the vortex appears and disappears repeatedly. It was not investigated if this happens with a certain frequency, since this was not an objective of this research. The behavior induced by the vortex is illustrated in figure 3 for a distance between the curtains ΔL = 0.8 m. As the distance increases again, the inner vortex continues to destabilize the curtains, but they stop intersecting with each other (fig. 4). The curtains were found to become stable when the distance was increased to ΔL = 2.0 m. As it can be seen in figure 5, the picture of the curtains remains almost unchanged at different time moments, the curtains showing only very slight oscillations. These oscillations and the curved paths of the curtains show that they are still influenced by the inner vortex. The effect of this vortex is enough strong to induce deviations of the curtains of about 1 m from the straight path. The results presented in figure 5 suggest also the stabilizing effect that the opposite fan inlets have on the curtains, by sucking the two air jets and thus forcing them to obey almost fixed trajectories.

It is clear that the initial rough estimation, which gave a minimum distance between the curtains of about 1.2 m, was quite far from the truth. However, the results we obtained suggest that one can still use this estimation if it is multiplied by a safety factor of 2.

3. Air curtains in the presence of a moving bus

In order to investigate how a large moving vehicle influences the behavior of the curtains, a solid having dimensions of a bus was introduced inside the computational domain after the dimensions of the domain were changed accordingly. The solid has a length of 11.5 m, a width of 2.5 m and a height of 3 m. It was placed on the right lane, at an initial distance of 8 m upstream from the first curtain and at 0.3 m away form the right wall and above the road, respectively. The lengths of the tunnel were changed to $L_1 = L_2$= 10 m. The distance between the curtains was set to ΔL = 2 m, which was found to assure the stability of the curtains. The width and height of the tunnel and the widths of the fan inlets and outlets were kept unchanged.

The movement of the vehicle was simulated using the sliding mesh technique. For this purpose two meshes were built. The first one is fixed and dicretizes the most part of the tunnel excepting a rectangular "hole". Through this hole can slide the second mesh, which encloses the vehicle. The two meshes are separated by special interfaces, whose treatment is described in the literature [10]. The initial shape of the computational domain, resulting from the initial position of the moving mesh, is presented in figure 6. As it can be seen, the two meshes overlap only partially. From a physical point of view, a perfect overlap is generally not possible, because the two meshes move relative to each other. Beside, the shape of the computational domain

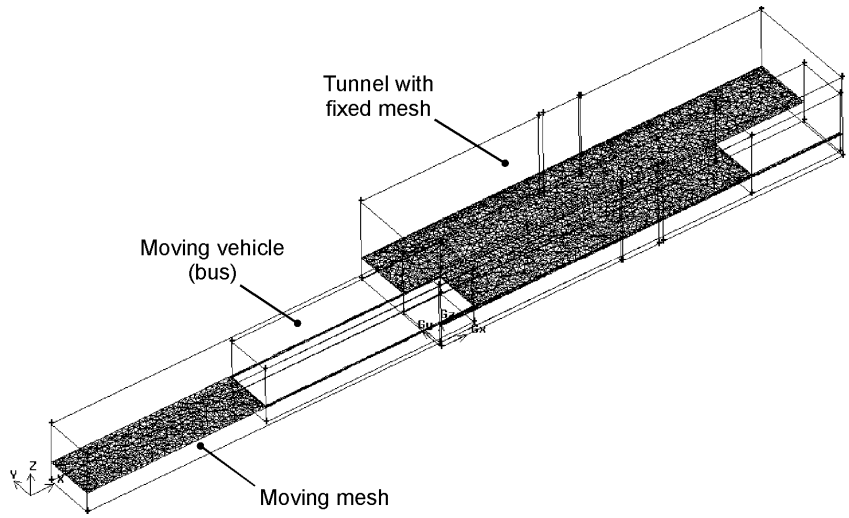


Fig. 6. Computational domain consisting of the fixed mesh of the tunnel and the moving mesh enclosing a large moving vehicle (bus); plane cut through the computational mesh.

changes from one time step to the other, while the moving mesh slides through the fixed one. To allow a good overlap of the two meshes for the most of the time steps, the sliding mesh was chosen longer then the fixed one.

Numerical simulations were carried out for four velocities of the moving vehicle: 5 km/h, 10 km/h, 20 km/h and 30 km/h. To keep the imposed brevity of this article, in the following only results obtained at velocities of 5 km/h and 30 km/h, respectively, are presented and discussed. The presented results consist in velocity vector fields plotted in a horizontal plane situated at 1.5 m above the road. When plotting the time dependent results the position of the camera was changed following the vehicle position.

The behavior of the curtains at different time moments when the vehicle velocity is 5 km/h is presented in figure 7. It can be seen that as long as the vehicle is still more meters away from the curtains they remain practically unperturbed (fig. 7a). The curtains begin to sense the effect of the vehicle when this closes within less than 2 m (fig. 7b and c). While the vehicle passes through them the curtains are of course disrupted (fig. 7d). However, it is to be noticed that, after being broken by the vehicle, the second curtain recovers quite fast and extends to the left side wall of the vehicle, thus maintaining to a certain extent the isolation of the upstream tunnel section (fig. 7d). The curtains begin to recover shortly after the vehicle leaves them behind (fig. 7e). In figure 7f, were the vehicle is about 6 m away, the curtains almost regained their stability. Considering the distance and the vehicle velocity, we can estimate that the time required in this case by the curtains to recover is less than 5 s. The conclusion we can draw is that in case of slow moving vehicles the curtains are accomplishing their desired role.

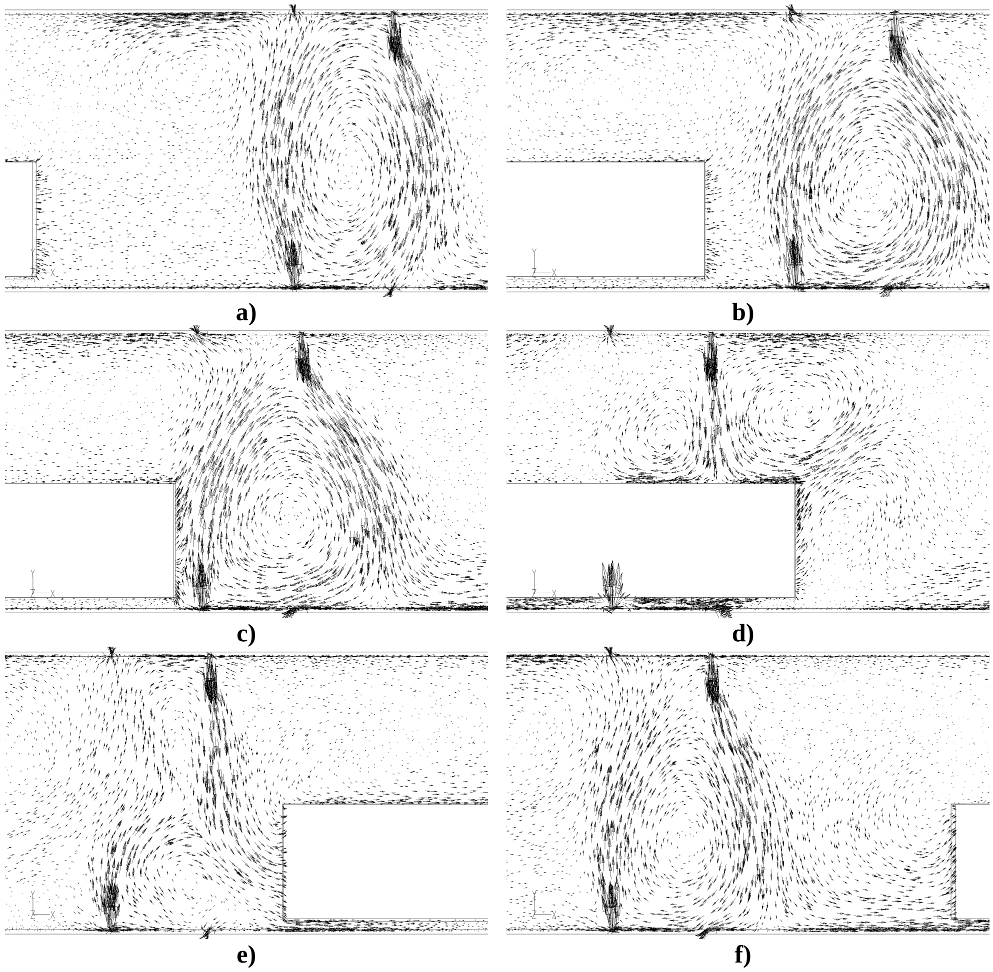
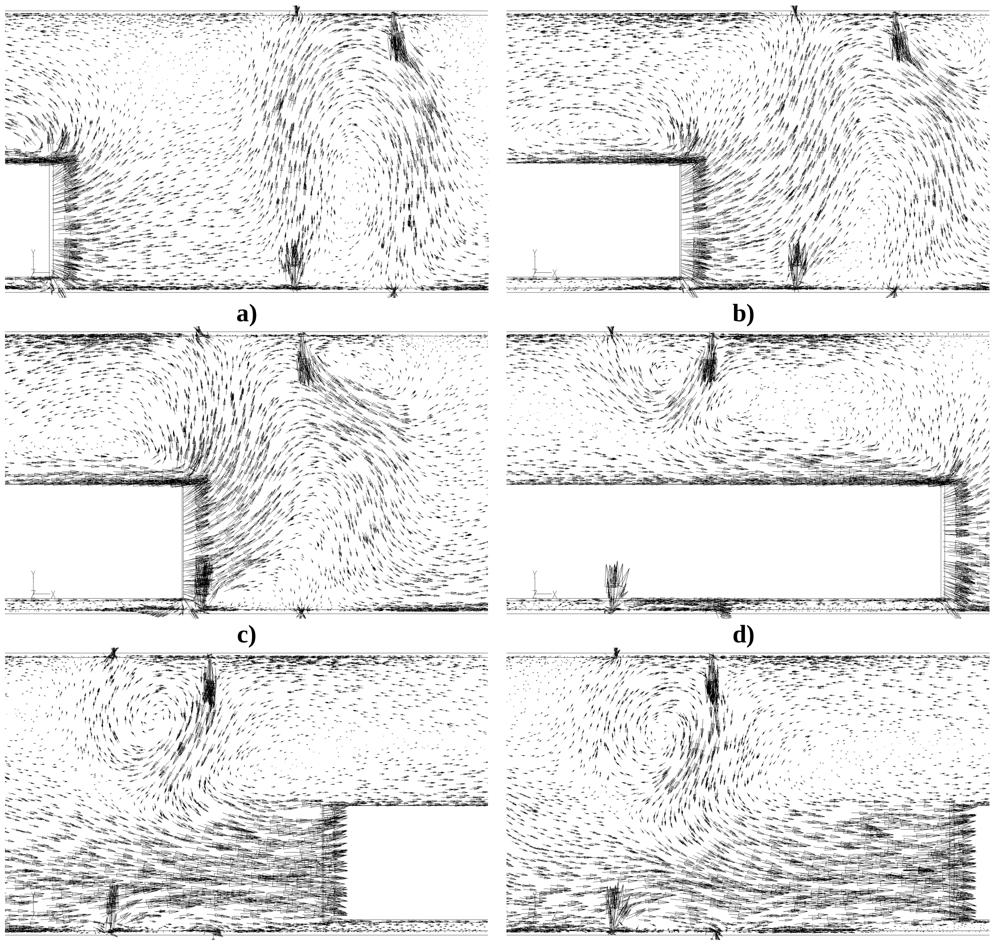


Fig. 7. Behavior of the air curtains when perturbed by a large vehicle (a bus) moving with a speed of 5 km/h.

For larger vehicle velocities the behavior of the curtains shows a noteworthy change. This fact, which was actually to be expected, is illustrated by the results obtained for a vehicle velocity of 30 km/h. Some of these results are presented in figure 8. The perturbation of the curtains can be already noticed when the vehicle comes in a range of about 6 m (fig. 8a). While the vehicle approaches the curtains still hold satisfactorily (fig. 8b) until the vehicle comes very close (fig. 8c) and breaks them. Because of the higher velocity of the vehicle, the curtains can not recover anymore while the vehicle traverses them (fig. 8d). Even when the vehicle departs, its strong wake continues to hinder the curtains from regaining their shape (fig. 8e and f). It was no more possible to estimate the time required by the curtains to recover, a longer sliding mesh being required for this

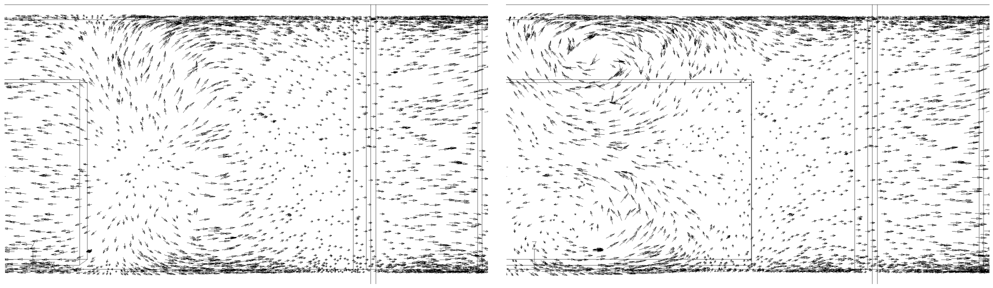


a) b) c) d) e) f)

Fig. 8. Behavior of the air curtains when perturbed by a large vehicle (a bus) moving with a speed of 30 km/h.

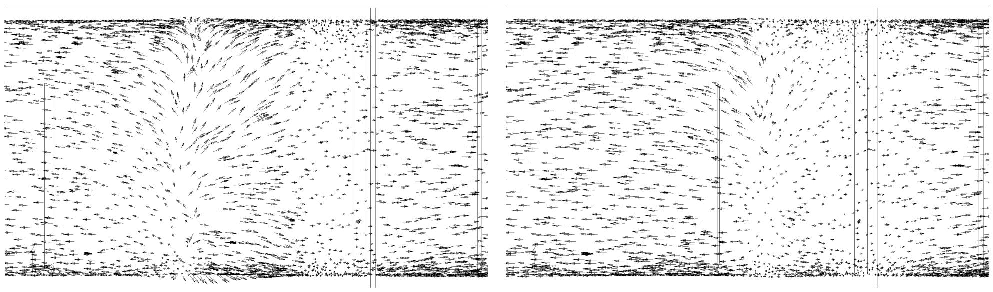
purpose. Nevertheless, we could conclude that, at least until being broken by the vehicle, the curtains are still fulfilling their desired role satisfactorily.

Of a great interest is also the flow of the air currents upstream of the first curtain. The structure of this flow should be taken into consideration when deciding where to place the intake of the ventilation fan. To gain an insight into this flow, velocity vectors in a vertical plane located to the left of the vehicle, along the axis of the left lane, were plotted for vehicle velocities of 5 km/h and 30 km/h. For the sake of clarity, the three dimensional vectors were plotted at the same length, independently of their magnitude. Figures 9 and 10 show these plots. As the vehicle approaches vertical currents may be noticed, which lift the air towards the ceiling (fig. 9a and fig. 10a). They only disappear when the vehicle comes at less than two



a) **b)**

Fig. 9. Velocity vectors upstream of the first air curtain, for a vehicle velocity of 5 km/h, plotted in a vertical plane situated at a distance of y = 4.5 m from the right wall of the tunnel.



a) **b)**

Fig. 10. Velocity vectors upstream of the first air curtain, for a vehicle velocity of 30 km/h, plotted in two vertical planes situated at a distance of y = 4.5 m from the right wall of the tunnel.

meters away from the first curtain. These currents are not significantly affected by the vehicle velocity. This velocity influences, however, the flow to the left of the vehicle. At small vehicle velocities two vortices appear in the vertical plane, one in the upper side of the tunnel, the other on the lower side (fig. 9b). These vortices disappear and the flow is directed backwards at larger vehicle velocities (fig. 10b). However, the position of the upper vortex observed at small velocities suggests that a proper place for the intake of the ventilation fan could be at about four meters upstream of the first curtain, where the vortex forms. This conclusion is based on the fact that vortices are expected to concentrate the pollutants.

4. Conclusions

In this article a modular ventilation of urban road tunnels was proposed. This type of ventilation makes use of transverse air curtains that allow to aerodynamically isolate tunnel sections from each other and from outside. Fresh air is introduced in each section and polluted air is sucked out and, after a cleaning process, is released to the atmosphere. In this way the appearance of regions in the tunnel with high concentrations of exhaust gases can be avoided and the increase of the pollution level in the vicinity of the tunnel portals can be hindered.

The solution proposed raises more questions, among which one concerning the stability of the curtains and another regarding the influence of moving vehicles on these curtains. Seeking answers to these questions, a study was carried out by means of numerical simulations. Its results suggest that, for the particular problem investigated, the minimum distance between the curtains, for which these curtains remain stable, is around 2 m. This distance is about two times longer than a rough estimation obtained by making use of results valid for single plane free jets. The results also showed that, when subjected to the influence of large vehicles moving at moderate speeds the curtains hold satisfactorily and accomplish their role until being broken by the vehicle. After this, the curtains are strongly perturbed by the moving vehicle, and, as the vehicle moves away, by its wake.

A suitable place for the intake of the ventilation fan seems to be at about four meters upstream from the curtains. However, further investigations are required to check if this placement will or will not have a destabilizing effect on the curtains and to what extent the curtains will be helped to regain their shape after being left behind by the moving vehicle.

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