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Modular ventilation with twin air curtains for reducing dispersed pollution

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ABSTRACT

The optimal solution for reducing the level of pollutants remains their trapping close to source. When this possibility is absent, the high degree of pollutant dispersion makes difficult and expensive any process of pollutant trapping and cleaning. This work suggests a new approach regarding the ventilation of urban road tunnels, based on the necessity for such spaces to take advantage of ventilation means which permanently direct the air towards cleaning filters while constraining uncontrolled pollutants dispersion. A concept of a modular ventilation is proposed, in which the air flow is not only induced by intake and/or exhaust fans and random obstacles inside the boundaries, but also confined by means of air curtains generated by cross flow fans. The expected result is a higher efficiency of the ventilation and of the subsequent air cleaning process. To illustrate the concept, a case study was undertaken. The investigations were focused on the behavior of twin air curtains generated by two cross flow fans and forming virtual walls inside an urban road tunnel. The results presented indicate how the distance between the curtains should be chosen, so that they remain stable, how the curtains interact with moving vehicles, and how the vents placed on the tunnel ceiling for exhausting polluted gases should be designed.

1. Introduction

Traffic congestions are nowadays a common problem in large cities. One way to address this problem is the construction of urban road tunnels. In many situations, such tunnels have hundreds of meters or even kilometers in length. Because of the pollution generated by vehicle exhausts, the air in long road tunnels must be properly ventilated in order to avoid impairing the health of the people traveling through the tunnel. This issue becomes increasingly important during rush hours, when the traffic becomes very slow. Also, the pollution level in the immediate vicinity of tunnel portals 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 or, at least, diminish the uncontrolled release of polluted air from the tunnel coupled with solutions for extracting and cleaning the air from inside the tunnel should be adopted when designing the ventilation system.

Four main types of ventilation systems are used in road tunnels: natural ventilation, transverse ventilation, semi-transverse ventilation (usually for supplying fresh air), and longitudinal ventilation. Long tunnels require either transverse, semi-transverse, or longitudinal ventilation. Transverse ventilation systems allow fresh air to be introduced and stale air to be removed uniformly throughout the tunnel (Jones, 2006). Moreover, Nishiuma et al. (2003) 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. (1996) 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. The main drawback of transverse ventilation is that it is the most expensive of the aforementioned ventilation systems. Chiu et al. (2003) 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 (Jones, 2006). 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 (Pucher and Sturm, 1985; Denk and Andorfer, 1997; Brousse et al., 2005), 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 (Smith, 2003). Despite its cost effectiveness, the longitudinal ventilation has in its turn other drawbacks. One drawback is that the concentration of exhaust 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, exhaust gases are pushed outside the tunnel through the exit portals, which leads to an increase in the pollution level in the vicinity of the portals.

In this work, an improved ventilation method is proposed, aiming at reducing the drawbacks of the traditional solutions in terms of efficiency and cost. The improvement is based on using twin air

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Nomenclature

b_i	width of the cross flow fans suction nozzles (m)
b_o	width of the cross flow fans discharge nozzles (m)
$b(x)$	width of a plane free jet (m)
C	constant for computing the half half-value width of a plane free jet (–)
H	height (m)
L	length (m)
ΔL	distance between the air curtains (m)
$\bar{p}$	average pressure (Pa)
p_0	reference pressure (Pa)
s	coordinate along a line inside the computational domain (m)
Δt	time step (s)
v_x	x-component of the velocity vector (m/s)
v_{x0}	initial jet velocity (m/s)
W	width (m)
x	coordinate along the symmetry axis of a plane free jet; coordinate along tunnel direction (m)
y	coordinate perpendicular to the symmetry axis of a plane free jet; coordinate perpendicular to tunnel direction (m)
$y_{0.5v}$	half half-value width of a plane free jet, i.e. local distance from the jet axis to the points with half the maximum velocity (m)
z	height above the road (m)
η	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ϑ_0	reference temperature (°C)

Subscripts

1	referring to the region upstream of the air curtains
2	referring to the region downstream of the air curtains
max	maximum value

curtains generated close to each other by means of paired cross flow fans. Each curtain is created at one of the walls and moves towards the opposite wall. The role of the air curtains consists in aeraulically dividing the tunnel into modules and separating them one from another and from the exterior. In this way, a modular ventilation becomes possible. This ventilation solution aims at hindering the flow of polluted air and at diminishing the diffusion of pollutants. The number of modules should be chosen depending on tunnel length, expected pollution level, and restrictions on the pollution level. Each tunnel module can be ventilated independently of the neighboring modules, being possible to adapt the ventilation parameters to the requirements of each module. Fresh air could be introduced in each tunnel module through vents placed upstream with respect to the direction of travel of the vehicles, which is the classical solution. Alternatively or additionally, in the frame of the proposed ventilation solution, fresh air could also be supplied through one or both of the twin cross flow fans. Polluted air could be extracted through exhausts placed downstream in each tunnel module, in order to keep local increases in pollutants concentration within the allowed limits. The air extracted from each module could, of course, undergo a cleaning process before being released into the outer atmosphere. At the same time, the air curtains placed at tunnel portals would restrict, at least to some extent, the uncontrolled release of pollutants in the neighboring areas. Thus, the common yet undesired dramatic increase in pollutants level close to long tunnel portals and the associated risk on public health when the tunnel is built in an urban agglomeration could be substantially limited. To illustrate the concept of modular ventilation, a simple schematic is presented in Fig. 1.

The reason for which adjacent twin air curtains are used instead of a single curtain comes from the expected benefits of this solution in terms of curtain stability and efficiency. Each air curtain is a plane free jet created in a cross-section of the tunnel. While the air in the jet moves towards the opposite wall, the jet section increases and the velocity decreases, which could reduce the efficiency of the curtain. If a single jet were used, it would have a very high initial velocity at nozzle exit in order to remain efficient. It should also be considered that the jet stability will suffer from the influence of air currents and moving vehicles. When using twin curtains, the two cross flow fans which generate them can be placed in the tunnel walls so that one's discharge nozzle faces the other's suction nozzle, i.e. so that the air blown by one fan is drawn by the other. In this way, each curtain could be better controlled. The jet growth and the decrease of the jet velocity are expected to be less significant. Consequently, the initial jet velocity could be lowered while still maintaining a high efficiency of the curtain. Also, the recovery of a curtain after being broken by a moving vehicle is expected to be faster.

The usage of cross flow fans to generate the curtains was chosen due to the benefits that come from the specific features of these fans. Their long runners with small radial dimensions can be used to create free plane jets of virtually any desired width or height. Moreover, the cross flow fans are able to deliver coefficients of discharge and pressure that are superior to those of axial and centrifugal fans in the discharge and pressure ranges required by ventilation systems.

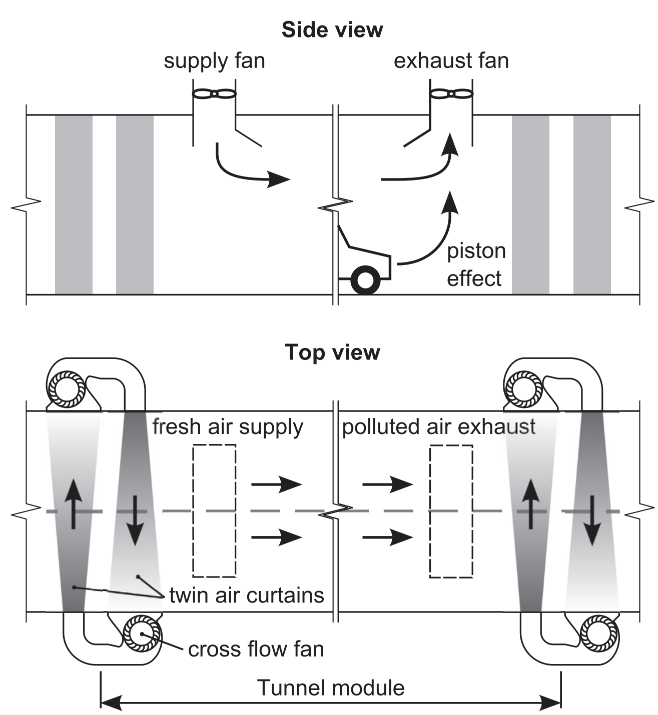

Fig. 1. Modular ventilation of a long urban road tunnel using twin air curtains.