J. Wind Eng. Ind. Aerodyn. 147 (2015) 66–76

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Flow field development and energy evolution in road tunnels with unidirectional uniform traffic

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ARTICLE INFO

Article history:
Received 20 July 2014
Received in revised form
14 September 2015
Accepted 14 September 2015
Available online 22 October 2015

Keywords:
Road tunnel
Air velocity
Energy
Distribution
Development

ABSTRACT

Shallow-buried road tunnel with roof openings is a green energy-saving technology. In this kind of tunnel, natural ventilation and natural smoke extraction can be realized through the roof openings. Now there are four shallow-buried road tunnels in Nanjing. Since operation, this kind of tunnel has been widely praised for the high air quality inside tunnel, but there is yet no regular design method of it. Buried section is the basic unit of this type of tunnel, while fully understanding of the development of flow field and velocity distribution is the foundation of solving the above problem. Based on simplified flow filed in the buried section and Prandtl velocity distribution law, this paper presented the formula of velocity distribution in the buried section. Besides, a 1/10 reduced-scale tunnel experiment platform was built to test the tunnel flow field on 9 kinds of traffic conditions. Energy transfer and dissipation law in the tunnel flow field were explained based on the concept of energy gradient and the formula of velocity distribution. Research showed that the velocity of the flow field increases quickly and then becomes stable with unidirectional uniform traffic. Velocity meets the logarithmic relationship with height. The air velocity in the tunnel varies approximately linearly with the vehicle speed. And the vehicle speed has much more influence on air velocity than the vehicle spacing. The energy transferred to the airflow from vehicles evolved into two parts in the flow field. One part is absorbed by the flow field and converted into the kinetic energy of the flow field itself. The other part is dissipated in turbulence. The kinetic energy increment increases with the height of the tunnel. The dissipation of energy along the tunnel presents an asymmetrical U-shaped distribution. When the flow becomes stable, the dissipation of energy also becomes stable, and the kinetic energy increment approaches zero.

1. Introduction

With the recent acceleration of urbanization, traffic problems are gradually becoming a more important factor. These problems influence urban development and ecological city building. In order to release some of the pressure created by increases in urban traffic, some cities build viaducts in urban areas. This helps to form rapid traffic aisles throughout the city. However, transportation networks composed of viaducts can have a large negative impact on the urban landscape. They can also create challenges for the protection of older town areas, and produce a large amount of traffic noise. As a beneficial supplement to above-ground traffic and rail traffic, the underground road tunnel can decrease or replace above-ground viaducts. In this way, they can improve overall urban traffic conditions. While dealing with the characteristics of urban traffic tunnels, Nanjing (China) has built four shallow-buried road tunnels with roof openings that adopt natural ventilation. This allowed for natural ventilation through the openings under normal operating conditions and a natural smoke extraction mechanism under fire situations. This completely abandoned the need for mechanical ventilation and mechanical smoke extraction. Although this kind of tunnel has been applied to actual projects, and obtained a sound practical effect, these project designs were based on qualitative analysis results. The natural ventilation tunnel with roof openings has not been given a more mature design methodology. In order to research on the mechanism and effect of ventilation of this kind of tunnel and realize the roof opening design, we must first understand the velocity distribution and the development process of the tunnel flow field. This study tries to clarify the development of flow field inside road tunnels as well as the transmission and dissipation of energy during this process with mathematical theories and experiments.

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http://dx.doi.org/10.1016/j.jweia.2015.09.011
0167-6105/

Nomenclature

U_1	air velocity in wall-affected zone, m/s
U_2	air velocity in vehicle-affected zone, m/s
U_3	air velocity in turbulence zone, m/s
U_0	traffic speed in the tunnel, m/s
κ	Karman constant, $\kappa = 0.4$
τ_1	air shear stress in wall-affected zone, N/m^2
τ_2	air shear stress in vehicle-affected zone, N/m^2
τ_3	air shear stress in turbulence zone, N/m^2
ρ	air density, $\rho = 1.179$ kg/m^3
υ	kinematic viscosity, $\upsilon = 1.539 \times 10^{-5}$ m^2/s
ε	roughness of vehicle surface, $\varepsilon = 1 \times 10^{-6}$ m
σ	measurement uncertainty, m/s
H	height of tunnel, m
h_υ	height of the interface between wall-affected zone and vehicle-affected zone, m
h	height of the zero point for the airflow in road tunnel, m
L	length of model vehicle, m
S	vehicle spacing, m

For the airflow in road tunnels, its flow properties and characteristics, such as the distribution of flow velocity and pressure, have not been systematically researched, and thus the research achievement is limited. Zabat et al. (1994, 1995) created a motorcade with 2, 3 and 4 Chevrolet Lumina vehicles at a reduced scale of 1/8. They performed a wind tunnel test in a Dryden window tunnel. Results here showed that when the distance between the vehicles in the motorcade was larger than twice the vehicle length, the flow field of the preceding vehicle was rarely influenced by other vehicles. Bellasio (1997) stated that the flow field in road tunnels was composed by two parts. Here, one part was related to atmospheric turbulence, and the other part was related to vehicle motion. Chen et al. (1998) researched the influence of moving vehicles on tunnel ventilation using a conveyor tunnel model with a reduced scale of 1/20. This research showed that a moving vehicle caused the axial flow of air inside the tunnel. The speed of the airflow was reduced with the height of tunnel, and the fastest airflow speed appeared near the vehicle. Sambolek (2004) tested the ventilation of the Sveti Rok Road Tunnel, and provided subsequent test results. Katolicky and Jicha (2005) established the Eulerian–Lagrangian model. They simulated the influence that moving vehicles (and vehicles inside a tunnel) had on ventilation. This was done by using CFD code StarCD. The numerical calculation results showed that the airflow velocity in a road tunnel was dictated by the moving speed of vehicles and the shape of the tunnel. Colella et al. (2009) developed a kind of tunnel ventilation analog computation and modeling method with low calculation costs. Wang et al. (2011, 2014) researched air pressure problems associated with an arc-shaped tunnel by taking advantage of the dynamic mesh technique. This research showed that the pressure of the flow field reached its largest extent at the head of the vehicle. It then decreased gradually with the increase of distance. An optimization model for traffic wind force on tunnel ventilation was also proposed by their team. Tong et al. (2014) established and solved an equation for airflow and pollutants in road tunnels. This was done on the basis of a one-dimensional and steady assumption.

Research done on energy evolution in the flow field of a road tunnel has, so far, been insufficient. The author of this paper was not able to find documentation directly related to this subject. However, research on energy gradients and dissipation in unsteady Couette flows can provide some theoretical reference for the research that was done in this paper. Taylor (1923) proposed a mathematical stability analysis for viscous fluids and compared results with those observed in the laboratory. The experimental study done by Coles (1965) and Andereck et al. (1986) showed that an increase in fluid viscosity could delay the change of a flow regime into a state of instability. Dou et al. (2007) proposed a calculation method for the energy loss mechanism and energy dissipation distribution in a Taylor–Couette flow. This was done between a plane Couette flow and a concentric rotating cylinder.

So far, the research has made some important achievements in the understanding of flow fields and ventilation inside road tunnels. It has revealed some characteristics and laws for flow fields. However, most of the research on flow field distribution in road tunnels depends on experimental data and numerical simulation techniques. Furthermore, even though there is a small amount of theoretical research, results have generally been obtained under the assumption of a one-dimensional and stable flow field. In this paper, the flow field of road tunnels in the research was divided into three areas according to the flow field characteristics. Based on the two-dimensional simplification of road tunnel flow field and the Prandtl velocity distribution law, velocity distribution formula for the three flow field partitions of the buried road tunnel was obtained. A 1/10 scale tunnel experiment platform was built, and the tunnel flow field was tested on 9 kinds of traffic conditions. Then the development of tunnel flow field and the velocity distribution rule were analyzed. On basis of the concept of energy gradient, the velocity distribution formula was utilized in the research to explain the energy transmission and dissipation rule in the road tunnel flow field.

2. Theoretical analysis

2.1. Simplification of airflow in shallow-buried road tunnels with the roof opening

The urban shallow-buried road tunnel with the roof openings can be regarded as the connection of various buried sections which are the basic units of this kind of tunnel. The airflow gradually develops in the buried sections and makes an exchange with the outside atmosphere at the roof opening at the end of buried sections. Supposing that the exchange of the airflow around the roof openings is adequate, and in reality, in order to ensure a good natural ventilation effect, the engineering design should also make the air inside and outside the tunnel fully exchanged in the opening. Then, the airflow in every buried section is similar to each other. Therefore, the study on the airflow in the whole tunnel converts to the research on the airflow in the buried sections (Fig. 1).

In addition, buried sections generally have the following three characteristics:

1. The length of the tunnel is much larger than hydraulic diameter, and in the unidirectional tunnels, the traffic is continuous and uniform.
2. Because of the large roughness height of automotive chassis and wake flow influence created by the preceding vehicle, the airflow turbulence between the chassis and the ground is strong. Here, the boundary layer of the road is thin.