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VEHICULAR TUNNEL VENTILATION DESIGN AND APPLICATION OF CFD

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ABSTRACT

Ventilation requirements for vehicular tunnels in the Hong Kong Special Administrative Region are discussed. For vehicle emissions, carbon monoxide is considered to be important for vehicles running on petrol engines, and suspended particulates for diesel engines. Other environmental control parameters are temperature, air speed and air pressure. Codes, regulations and design guides for ventilation systems are reviewed. Different ventilation designs adopted in local vehicular tunnels are described. Better ventilation design for a typical vehicular tunnel is proposed with the application of Computational Fluid Dynamics. Numerical experiments on different cases including designing longitudinal ventilation system for smoke control were performed to justify the indoor environment.

KEYWORDS

Tunnel, Ventilation, Carbon Monoxide, Computational Fluid Dynamics (CFD).

INTRODUCTION

Efficient transportation network has always been a key factor contributing to the success of the Hong Kong Special Administrative Region (HKSAR) as a trade, business and finance centre. Many tunnels are constructed in the HKSAR. Healthy and safe environment is the utmost concern of the general public, and an even big challenge to building services engineers. The design criteria of the environmental control system for tunnel shall take into account the normal operating and emergency conditions. In normal operating condition, a healthy and comfortable environment shall be provided for passengers and for personnel working there. Sufficient air circulation through fresh-air inlets shall be provided. An upper limit of carbon monoxide (CO) level is assigned in a vehicular tunnel with a summary presented by Chow and Li (1999). Typical figures are:

- CIBSE Guide E (1997): 6000 ppm incapacity and 12000 ppm death for 5 minutes exposure; and 1000 ppm incapacity and 2500 ppm death for 30 minutes exposure.

- NFPA130 (1997): less than 800 ppm during smoke condition in air with greater than 20% oxygen content for 30 minutes evacuation period.

- ASHRAE (1989, 1995): maximum 120 ppm (137 mg/m^3) for 15 minutes exposure time; maximum 65 ppm (65 mg/m^3) for 30 minutes exposure time; maximum 45 ppm (45 mg/m^3) for 45 minutes exposure time; maximum 35 ppm (35 mg/m^3) for 60 minutes exposure time; and less than 125 ppm for maximum of 1 hour exposure time; all in tunnels located at or below an altitude of 1500 m.

- Permanent International Association Road Congresses (PIARC, 1991): 100 to 150 ppm for urban tunnel (daily congestion, seldom congested and highway or mountain) for smooth traffic; and for congested traffic or standstill, 100 to 150 ppm for urban tunnel (daily congestion); 150 to 250 ppm for urban tunnel (seldom congested); and 150 to 200 ppm for interurban tunnel (highway or mountain).

- Practice Notes on Control of Air Pollution in Vehicle Tunnels (Hong Kong Environmental Protection Department, 1990): 100 ppm for 5 minutes average exposure time.

Passenger comfort can be evaluated with regard to air temperature, air velocity and air pressure. They are critical factors for ventilation design, and to some extent, for fire safety as well. In an emergency, the ventilation system in the tunnel shall ensure smoke and heat of a fire is kept away from people who might be trapped in the tunnel. Therefore, the direction of smoke movement shall be controlled, and a smoke-free path shall be provided for passenger evacuation and for firefighting operations.

ENVIRONMENTAL CONTROL SYSTEM FOR TUNNEL: DESIGN PARAMETERS

Petrol and diesel engines produce toxic and carcinogenic exhausts including CO, particulates, unburnt hydrocarbons, oxides of nitrogen and sulphur of different relative proportions. CO is taken as one of the criteria in ventilation design in tunnels because of its higher concentration.

Natural or mechanical ventilation systems are required for transit systems. Air temperature control for passenger comfort in the station can be achieved by circulating ambient air in moderate climates, and optimum operating conditions for the specific equipment should be ensured. Most importantly, it is essential to distribute air to control smoke and reduce air temperature to permit passenger evacuation and fire-fighting operations. Apart from these, air pressure in tunnel also affects the safety of passengers. If too much air is delivered into the escape route, over-pressurization of the space can occur, leading to difficulty in opening doors to the escape route such as cross passageway. A summary of the control of those three parameters on air temperature, velocity and pressure was presented by Chow and Li (1999).

Smoke control is another determining factor in the design of ventilation equipment, such as clear height, visibility and optical density of smoke should be considered and the tenable values should be maintained for a short time. A summary of the key points on smoke control aspects appeared in international standards was presented earlier by Chow and Li (1999). Locally, smoke free zone of 2.5 m high is required; and reduced to 2 m is required by Fire Services Department (1998). Dynamic smoke extraction systems should be provided where the tunnel is longer than 230 m.

VENTILATION DESIGN

Ventilation may be provided by natural means, by the traffic-induced piston effect, or by mechanical equipment. Natural and traffic-induced ventilation is adequate for relatively short tunnels and tunnels with low traffic density. Long and heavily used tunnels should have mechanical ventilation. Different mechanical ventilation systems are adopted for the vehicular tunnels in the HKSAR as shown in TABLE 1.

CO is the contaminant usually selected as the prime indicator of tunnel air quality. On ventilation aspect, the design of ventilation systems for tunnels requires engineers to establish the standard to which CO should be controlled. Also, engineers should focus on vehicle emission data in order that reasonable estimates can be made from source strengths and rates, and hence permit the appropriate ventilation measures to be taken.

TABLE 1

TYPES OF VEHICULAR TUNNEL VENTILATION SYSTEM IN THE HKSAR

Ventilation System	Characteristics	Examples of Tunnel	Tunnel Length/km	Remarks
Jet fan longitudinal ventilation	Airflow along tunnel is created by jet fans at a limited no. of points	Cheung Ching Tunnel Shing Mun Tunnel - Smugglers Ridge - Needdel Hill Tseung Kwan O Tunnel	1.6 1 15.6 0.89	3 jet fans installed on 110m centres 16 jet fans 24 fans 8 pairs of booster fans installed on 100m centres
Full transverse ventilation	Fresh air supply uniformly and equals to extracted vitiated air	Lion Rock Tunnel	1.4	has been modified to combined ventilation system
Semi-transverse supply ventilation	Fresh air supply uniformly along the tunnel through air duct	Cross Harbour Tunnel Tate's Carin Tunnel	1.86 3.95	$955 m^3/s$ of fresh air is supplied to each tube 6 reversible ventilation fans in each ventilation building at both ends of tunnel
Partial transverse ventilation	Fresh air supply greatly equals to extracted vitiated air	Aberdeen Tunnel Eastern Harbour Crossing	2.1 2.2	 16 supply fans and 10 exhaust fans
Combined ventilation		Airport Tunnel	1.4	longitudinal and semi-transverse system

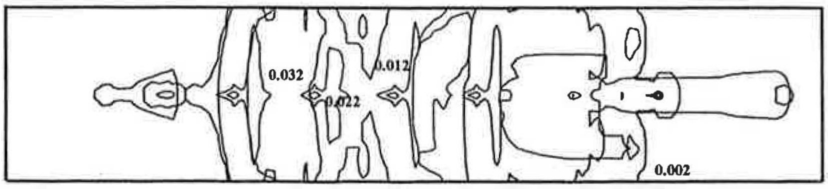
CASE STUDY

A tunnel linking Kowloon and Shatin was used as an example. Mechanical ventilation system adopted in this tunnel was full transverse ventilation originally. Full transverse ventilation includes both a supply duct and an exhaust duct to achieve uniform distribution of supply air and uniform collection of vitiated air throughout the tunnel length. With this arrangement, contaminant concentration along the roadway is uniform. Under low unidirectional traffic flow, the ventilation system can be turned off, and natural ventilation is utilized; or the system can be used in semi-transverse mode with the operation of fresh air fans only. In order to cope with the growing traffic flow and improve the tunnel environment, the tunnel was modified to become a combined ventilation system in 1994. Longitudinal ventilation is achieved with additional axial fans (jet fans) mounted at the tunnel ceiling, so that the contaminant concentration increases along the tunnel.

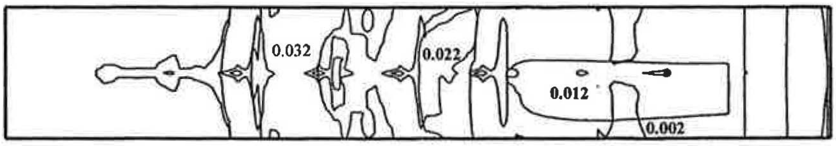
There are dispersion models for evaluating the potential air quality effects of mobile emission sources. Dispersion modeling can address the impact of pollutant emissions, for example, the concentrations of mobile source CO emissions can be calculated for roadway segments. The pollutant source strengths depend upon specific emission characteristics from vehicles and the patterns of use. Higher CO emissions can often be encountered during "stop-go" driving in urban traffic. For this tunnel, linking Shatin, a big urban area with population over 1 million, and other parts of the New Territories to Kowloon, there is always a heavy traffic load on it. Consider a condition that cars are running slowly at about 8 km/h and keeping at least "two-second" driving distance, the CO emission and dispersion characteristics can be estimated. According to ASHRAE (1995) Application Handbook, the predicted hot emissions of CO for an individual car of assumed speed 8 km/h is 0.0315 g/s in summer (32°C).

APPLICATION OF CFD

Ventilation system for a typical vehicular tunnel can be designed with the aid of Computational Fluid Dynamics (CFD) (e.g. Chow 1996). CFD is now a useful design tool for building services engineering in predicting the distribution of environmental parameters including velocity vectors diagram. The tunnel discussed above of length 1425 m, width 8.5 m and height 4 m was taken as an example. The FLAIR menu of PHOENICS version 3.2 was used (CHAM 1999). There, standard k-ε model was used to simulate the turbulent effect. This model had been validated extensively with reports appeared in the literature (CHAM 1999). The CO dispersion contours (in fraction of source strength) under natural ventilation and 6m/s longitudinal ventilation are shown in Figure 1.



(a) natural ventilation



(b) 6 m/s longitudinal ventilation

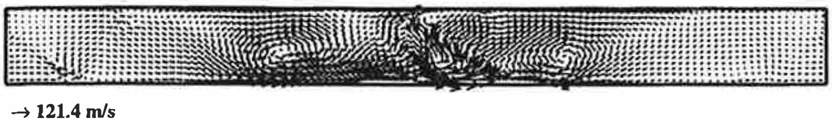
Figure 1: CO dispersion

Results illustrate that CO concentration will increase from ambient level at the entering portal to a maximum at the exiting portal. This is effective where traffic is unidirectional, however, adverse external atmospheric conditions can reduce the effectiveness of this system. Figure 4 also shows that the longitudinal airflow created by the mechanical ventilation system gives little effect to the CO dispersion behavior at low level. In this case, the cars are running slowly with speed less than the limit of 70 km/hr. In this way, airflow induced by the piston effect would be very low. Therefore, it is difficult to reduce the contaminant levels without operating the mechanical system.

LONGNITUDINAL VENTILATION SYSTEM FOR SMOKE CONTROL

For sizing the longitudinal ventilation system for smoke control, a 38 MW fire of size 7.3 × 7.3 m × 1 m located at the middle of the tunnel was considered. The heat output of the fire was constrained to follow the fuel spillage fire size estimation of a truck (e.g. Ingasson 1994). As the tunnel is too long, only a section of 50 m was considered. The predicted flow fields under natural ventilation are illustrated in Figure 2.

(a) Temperature (in °C)

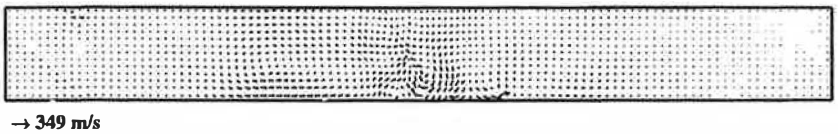


(b) Velocity vector

Figure 2: Predicted result for 38 MW fire

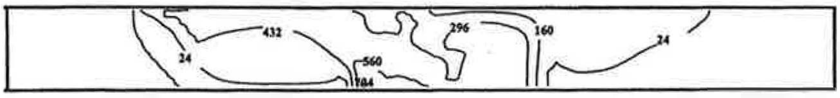
Depending on the ventilation condition, for at least 3 m/s longitudinal ventilation, the heat release rate increased to 61 MW. This was explained before by Chow (1998) due to the large volume of air drawn to the burning object would facilitate combustion to give higher heat output. In order to create longitudinal tunnel airflow and prevent the propagation of smoke and heat to the trapped traffic, the back-layering phenomenon, 6 m/s longitudinal ventilation was then applied. The predicted results of both cases are shown in Figures 3 and 4.

(a) Temperature (in °C)

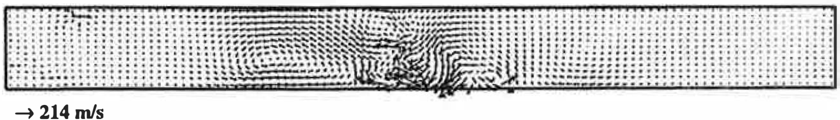


(b) Velocity vectors

Figure 3: Predicted results for 61 MW fire under 3 m/s longitudinal ventilation



(a) Temperature (in °C)



(b) Velocity vector

Figure 4: Predicted results for 61 MW fire under 6 m/s longitudinal ventilation

CONCLUSION

Different tunnel design standards and criteria are reviewed. The turbulent air movement induced by thermal sources inside a tunnel is investigated. With the application of CFD, engineers are not only able to design a tunnel ventilation system that fully complies with the statutory requirement, but also achieve a design acceptable by the local authority.

ACKNOWLEDGEMENT

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