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Performance validation of a hybrid ventilation strategy comprising longitudinal and point ventilation by a fire experiment using a model-scale tunnel

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ABSTRACT

We examined the exhaust performance of a hybrid ventilation strategy for maintaining a safe evacuation environment for tunnel users in a tunnel fire. The hybrid ventilation strategy combines the longitudinal ventilation strategy with the point ventilation strategy which is a type of transverse ventilation strategy. The model tunnel developed by this study was scaled to 1/5 the size of a full-scale tunnel. The model-scale experiment was performed taking into consideration Froude's law of similarity. Measurement items were the distribution of temperature and concentration of smoke inside the tunnel, longitudinal wind velocity, mass flow of smoke in the point ventilation duct, and the heat release rate of the fire source. The following main conclusions were obtained. The smoke height was constant even when varying the extraction rate of smoke from the ceiling vent. The backlayering length and critical velocity of the smoke flow in the hybrid strategy could be predicted by the methodology developed by using the longitudinal strategy. The hybrid strategy maintained a safe evacuation environment on both sides of the tunnel fire.

1. Introduction

A mechanical ventilation system installed in a tunnel has two important functions in a fire situation. First, the system protects the lives of tunnel users by allowing them to evacuate from the tunnel. Next, the system gives firefighting and rescue service personnel a clear path to the site of the fire. The types of mechanical ventilation system are selected considering the length of the tunnel and the traffic type (bidirectional or unidirectional), and the possibility of congestion. Two types of ventilation system are mainly used for ventilation in a normal situation and in a fire situation in the tunnel. Generally, unidirectional tunnels (e.g., expressway tunnels) adopt a longitudinal ventilation strategy that blows parallel to the direction of vehicle travel, as shown in Fig. 1(a). This strategy pushes all the smoke produced by a burning vehicle to one side of the fire, and breaks up the smoke stratification under the ceiling of the tunnel. However, users located on the downstream side of the fire are exposed to the smoke, which includes toxic gases and also reduces visibility. Therefore, although the longitudinal ventilation strategy is simple and inexpensive, it is dangerous to use in bidirectional tunnels and congested tunnels. The transverse ventilation strategy, as shown in Fig. 1(b), provides more advantages than the longitudinal strategy in a fire situation. The smoke from a fire is buoyant and thus concentrates in the upper part of the tunnel space. The transverse ventilation strategy uses vents on the ceiling of the tunnel to extract the smoke. This strategy can avoid destratification of the smoke and excessive longitudinal spread of the smoke, and so maintains a relatively safe refuge for tunnel users. However, this strategy is generally complex and expensive [1]. The hybrid strategy combines the longitudinal ventilation strategy and point ventilation strategy. Fig. 1(c) shows the smoke exhaust condition using the hybrid strategy in a fire situation. The point ventilation strategy, which is a type of transverse ventilation strategy, uses a large vent on the tunnel ceiling. The hybrid strategy will, like the transverse ventilation system, probably be able to maintain a safe evacuation environment on the downstream side of a fire.

Vauquelin and Megret [2] carried out tunnel fire experiments using a reduced scale model equipped with two mechanical exhaust vents on both sides of the fire source. This exhaust strategy was equivalent to the two-point extraction strategy, which is a type of transverse ventilation strategy. Their experimental setup was characterized by the use of a low-density gas (a mixture of air

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Nomenclature

A	cross-section of tunnel [m^2]
C_p	specific heat at constant pressure [J/kg K]
Cs	concentration of smoke [dimensionless]
D	effective diameter of a fire vessel [m]
Fr	Froude number $Fr = U/\sqrt{gH}$ [dimensionless]
g	gravitational acceleration [m/s^2]
H	height of tunnel, characteristic length [m]
$\bar{H}$	hydraulic tunnel height, modified characteristic length $\bar{H} = 4A/Ws$ [m]
k	extinction coefficient [1/m]
L	optical path length, corresponding to tunnel width [m]
L_b	backlayering length of thermal fumes [m]
m_e	mass flow rate of smoke flowing under a tunnel ceiling [kg/s]
m_p	mass flow rate of smoke produced by a fire [kg/s]
m_∞	maximum mass burning rate per unit area [kg/m^2 s]
M	mass flow rate of point ventilation [kg/s]
Q	heat release rate [kW]
R	regression rate of a pool fire [m/s]
Re	Reynolds number $Re = UH/\nu$ [dimensionless]
S_h	height of boundary between thermal fumes and fresh air [m]
S_t	thickness of smoke [m]
T	temperature [K]
U	velocity, characteristic velocity [m/s]
V	volume flow rate of point ventilation [m^3/s]
W	width of tunnel [m]
W_s	tunnel wetted perimeter [m]
ΔT	temperature rise from ambient temperature [K]
ΔT_{avg}	temperature difference between the average temperature and ambient temperature [K]
ΔT_{cf}	temperature difference between the ceiling temperature and the floor temperature [K]
β	mean-beam-length correction [dimensionless]
γ	scale ratio [dimensionless]
ν	kinematic viscosity of air [m^2/s]
ρ	density [kg/m^3]

Subscripts

c	critical condition
full	full-scale tunnel
model	model-scale tunnel
s	smoke
$*$	dimensionless parameter
0	ambient condition

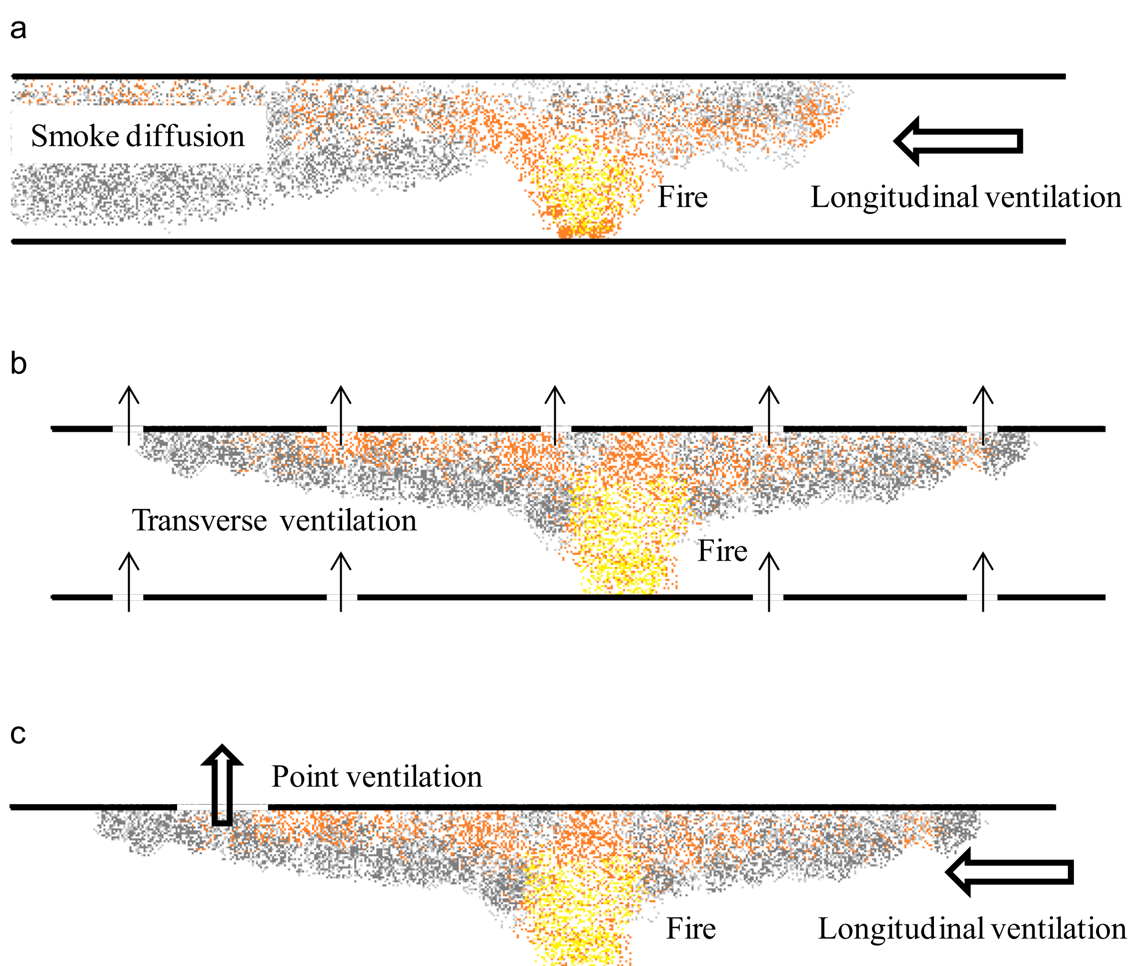

Fig. 1. Schematic representation of ventilation strategy. (a) Longitudinal ventilation strategy, (b) transverse ventilation strategy, and (c) hybrid ventilation strategy.