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Smoke movement in tilted tunnel fires with longitudinal ventilation

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ABSTRACT

Studies on smoke movement in a tilted tunnel fire with longitudinal ventilation will be reported in this paper. Analytical equations on fires acting at the smoke layer were studied first. Numerical simulations with Computational Fluid Dynamics (CFD) were carried out. Physical scale modeling experiments were performed to study the critical velocity for preventing back-layering in a tunnel model with tilted angles at 0°, 3°, 6° and 9° to the horizontal. Froude number modeling was used to deduce empirical formula on the location of smoke stagnant point under longitudinal ventilation. The normalized heat release rate $\dot{Q}''$ is a key factor and the critical value of $\dot{Q}''$ is 0.12. This study was focused on $\dot{Q}''$ less than 0.1 while deriving the relations between critical velocity and heat release rate. The results are similar to some findings reported earlier in the literature. Non-dimensional critical longitudinal velocity for preventing back-layering effect was found to be varied with heat release rate to the power 1/3. The critical velocities for preventing back-layering for tilted tunnels are higher than the values required for horizontal tunnels. However, a corrected empirical formula for critical velocity in a tilted tunnel is proposed based on the experimental and numerical results.

1. Introduction

Many long tilted railway and vehicular tunnels were constructed in hilly areas in Mainland China, Hong Kong and Taiwan [1,2]. Smoke control systems [3] are specified in some of these newly constructed tunnels. However, smoke movement is not fully understood in tilted tunnels with assumed smoke pattern [4]. The fire scenario, occupant loading, education and fire safety awareness of citizens, local firefighting provisions, etc., of many places in the Far East are all different from those of the advanced countries. The fire codes and regulations e.g. [5–7] for tunnels, bridges or others in advanced countries cannot be applied directly without justification of the scenarios assumed. Therefore, these fire codes and practices can only be taken as references. Due to the uniqueness and the differences with the advanced countries, there must be justifications [8] for adopting the selected fire hazards and associated assumptions made in those overseas codes to the Far East countries.

For a tunnel inclined at an angle θ to the horizontal, hot smoke would move up along the longitudinal axis with acceleration gsin θ [2,9]. This acceleration would affect smoke movement and should be considered when designing smoke control systems. All the presumed smoke movement patterns [4] for some tilted tunnels or long corridors should be justified by experiments, at least with scale modeling tests [10]. Note that smoke movement patterns in horizontal tunnels have been studied thoroughly, but not for smoke movement in a tilted tunnel. Therefore, smoke movement pattern in a tilted tunnel was studied and reported in this paper.

Empirical expressions on critical velocity upon operation of longitudinal ventilation system were derived [11,12] using Froude number models on horizontal tunnel experiments. Numerical studies on tilted tunnels suggested [13] that the tilted angle and ceiling height are two key factors affecting smoke movement and hence the control by longitudinal ventilation. Stack effect should be considered [14] in ventilation design for tilted tunnels with angles in excess of 1–2%. Experimental results [15] showed that the critical velocity for tilted tunnels at angles from 0° to 10° was higher than that for horizontal tunnels. The empirical formula calculating critical velocity in tilted tunnels should be corrected.

Smoke control by longitudinal ventilation in a tilted model tunnel was studied and will be reported in this paper. Smoke movement in a tilted tunnel was studied analytically with available empirical formula reviewed. Numerical experiments with Computational Fluid Dynamics (CFD) were carried out. In this paper, smoke movement in a scale tunnel model was studied to justify the results [2,9,10]. Experiments with physical model can

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Nomenclature

a	heat transfer coefficient (W m^{-2} K^{-1})
A	cross-sectional area (m^2)
b	tunnel width (m)
c_f	friction coefficient
C_p	specific heat (kJ kg^{-1} K^{-1})
d	counterflow distance (m)
D	pool diameter (m)
e	natural constants
f	perimeter (m)
Fr	Froude number
g	gravity acceleration (m s^{-2})
h	smoke layer height (m)
H	tunnel height (m)
k	temperature decay coefficient
L	characteristic length (m)
$\dot{m}$	fuel mass loss rate (kg m^{-2} s^{-1})
P	pressure (Pa)
$\dot{Q}_L$	heat loss rate in Appendix A (kW)
$\dot{Q}$	heat release rate (kW)
Ri	Richardson number
S	smoke stagnation point
t	time (s)
T	temperature (K)
u	smoke velocity in Appendix A (m s^{-1})
u_0	natural air velocity in Appendix A (m s^{-1})
V	longitudinal ventilation velocity (m s^{-1})
w_e	horizontal air entrainment coefficient
x	coordinate in longitudinal axis direction (m)

Greek symbol

α	tunnel slope (°)
β	entrainment coefficients from Kunsch [40]
ε	experimental coefficients in maximum temperature equation from Kurioka [25]
ρ	density (kg m^{-3})
γ	experimental coefficients in maximum temperature equation from Kurioka [25]
θ	tunnel inclined angle
τ	friction stress (N m^{-2})
Δ	difference between two positions

Superscript

$-$	characteristic variables
$''$	non-dimensional variables

Subscript

buoyancy	variables caused by buoyancy
cr	critical
0	ambience
s	static
d	dynamic
max	maximum value
m	modified
r	reference value above the fire source
total	total value
x	*x* direction
w	wall

give the results of real fire scenarios. However, full-scale burning tests are very expensive, and it takes a long time to carry out the tests and compile the reports. More importantly, it is difficult to reproduce and repeat the experiments. Scaled experiments can be adopted if appropriate scaling factors are preserved, say Froude number modeling for smoke movement. Scale models are very suitable for studying smoke movement and post-flashover room fire with appropriate scaling factors as suggested by Quintiere and updated recently [10,16]. This method has better repeatability and reproducibility and is used in this paper. However, using only the scale modeling experimental data is not good enough. There are limitations on the test rig installation and accuracy of the measured variables. Therefore, CFD is adopted together with scale modeling tests to explore the smoke movement characteristics with appropriate boundary conditions and to derive empirical formula among the variables of interest. The relationship between d and V_{cr} in a tilted tunnel was studied using Froude number modeling technique. Results by Atkinson and Wu [15] will be referred to and supported by physical scale model experiments and CFD predictions. The CFD software Fire Dynamics Simulator (FDS) [17] is used in this paper. FDS is widely used in studying building fires [18–25].

As reported by Cai and Chow [21] in using FDS 5.0.0 for studying liquid pool fire under different ventilation conditions, the averaged predicted HRR by the liquid fuel model in FDS 5.0.0 did not agree with the experimental results. The upgraded version FDS 5.5.3 with liquid fuel and gaseous products using appropriate thermophysical properties was used in this paper to simulate the combustion process of liquid fuel. More realistic boundary conditions on air inlet can be specified in FDS 5.5.3. All the numerical schemes associated with solving the coupled differential equations are modified. In addition, FDS 5.5.3 is capable of simulating the transient fire induced phenomenon in most cases within the expected accuracy [22]. Predictions agreed well within the experimental uncertainty with a prescribed heat release rate. FDS 5.5.3 can give realistic smoke transport and is able to predict reasonable results for fire simulations [23,24]. In studying gasoline open pool fires [25] with experimental validation under different pool diameters, FDS 5.5.3 can simulate the nonpremixed flames for complex fuel such as gasoline. Therefore, studying gasoline fires in tunnels by FDS 5.5.3 as in this paper will give reasonably good predictions on justifying empirical equation [15] with experimental support.

2. Application of Froude number model

In a tunnel fire, the buoyancy-induced axisymmetric plume gives a ceiling jet after striking at the ceiling. Longitudinal ventilation was designed to drive smoke to one end of the tunnel. There will be back-layering effect when the longitudinal velocity V is less than a critical value V_{cr} as shown in Fig. 1. Increasing V to a value higher than V_{cr}, smoke would be pushed to the other tunnel end. The value of V_{cr} is a key design parameter for longitudinal ventilation smoke control system [12,26–28].

Buoyancy is the key driving force for smoke movement. Froude number Fr is the ratio of inertial force to buoyancy, expressed in terms of characteristic velocity V, characteristic length L and g as reported in the literature [10,16]: