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짧은 터널 내의 연기거동에 관한 연구

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A Study of Smoke Movement in a Short Tunnel

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Abstract. This paper concerns smoke propagation in tunnel fires with various size of fire source. Experiments carried out in model tunnel and those results were compared with numerical results. The Froude scaling law was used to scale model tests for comparison with larger scale tests. In order to validate for numerical analysis, temperature distribution of predicted data was compared with measured data. Examining the temperature distribution, we found that smoke layer does not come down under 50% of tunnel heights for a short tunnel fires without ventilation. Front velocity of smoke layer is proportional to the cube root of heat release rate. And it is in good agreement with existing empirical expression and numerical prediction. In a short tunnel fire, horizontal propagation of smoke layer is more important than vertical smoke movement for evacuation plan.

Key words: Fire safety, Buoyant flow, Heat and mass transfer, numerical analysis, Fire experiment.

초 록. 터널화재시 화원의 크기에 따른 연기기동을 파악하기 위하여 모현실험 및 수치해석이 수행괴었다. 모형실험의 결과를 실제 터널에 대해 적용하기 위하여 Frode상사법을 이용하였다. 터널공간내의 화재 해석에 대한 수치해석의 타간성을 입증하기 위하여 모형실험과 수치해석에서 얻어진 연층의 온도분포를 비교하였다. 터널내 온도분포를 해석함으로써 배기장치가 없는 짧은 터널에 대하여 연층은 전체 터널 높이의 절반 이하로 하강하지 않는다는 사실을 파악하였다. 또한 실험에서 얻어진 연층선단의 전파속도는 화재 발생부의 1/3층에 비례한다는 사실을 파악하였으며 이는 기존의 경험식 및 수치해석결과와도 잘 일치하였다. 따라서 짧은 터널에서 화재시 피난대책을 수립하는데 있어서 연층의 수평전파가 수직전파에 비해 중요한 설계변수임을 본 연구를 통하여 제시하였다.

핵심어 : 화재실험, 화재안전, 부력유동, 열 및 물질전달, 수치해석

1. Introduction

In Korea, a country of 70% occupied with mountainous district, a large number of rail and road tunnels will be constructed in the coming decade, hence safety plan is important subject for tunnel design. Although a fire in tunnel does not break out frequently, it causes a serious accident with massive development of heat and combustion gases. Actually many accidents have been reported from France, UK, and various parts of the world. In order to establish the pertinent emergency plan, heat and smoke movement in tunnel must be analyzed from experimental and numerical approaches. Various studies of tunnel fire have been reported from 1970s, but most of the previous researches as were focused on ventilation problem with fire source. Y. Oka and G. T. Atkinson carried out experimental study with model tunnel, the results have revealed significant limitation on the utility of existing empirical expressions for the critical velocity.1) W. K .Chow reported the use of zone model for simulating tunnel fire and the results are compared with a self-developed field model and experimental results.2) S. Miles and S. Kumar have demonstrated that CFD fire model with ventilation effect was validated with full-scale fire tests from the Memorial Tunnel Fire Ventilation Test Program.3) I. Riess and M. Bettelini suggested a one dimensional time dependent model for tunnel fires with longitudinal ventilation.4) As described above, many works for tunnel fires were focused on ventilation effect. To make good use of the ventilation system, more detailed study for smoke spreading

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mechanism is required to accumulate the knowledge for tunnel fires. In particular, smoke propagation in tunnel without ventilation effect seems to be a worthwhile subject to investigate for bases of many other tunnel fire research. Hence the present paper deals with the problem of smoke movement and temperature distribution in tunnel fires. Experiment carried out through model test and numerical results were obtained from CFD simulation. The mechanism of smoke movement in tunnel fire is analyzed by comparison of both results. These comparisons will be a useful database for evacuation plan for tunnel fires.

2. Experimental and Numerical Model

2.1 Model Tunnel

Smoke spreading tests were performed in a model tunnel which is 9 m long, 0.4 m wide and 0.4 m height. The material of all sides of tunnel consisted of a 12 mm acrylic board. Temperature distribution in tunnel was measured with T-type thermocouples (Copper-Constantan) which ranged from -270 to 400°C. The thermocouples were mounted at each station at heights 4, 8, 12, 16, 20, 30 cm below the ceiling. In order to measure the horizontal smoke propagation, TC1-TC8 was mounted 20 mm below the ceiling. Both portals of tunnel were fully open. Fig. 1 shows an axial cross-section of the experimental setup.

2.2 Fire Source

Four different sizes of pool which is 2.2, 3.55, 4.36 and 5.23 cm diameter were used in the test series(Table 1). Fire source was placed in the center of tunnel. The heat release rate was determined by multiplying the heat of combustion with a fuel evaporation rate. For a gasoline pool fire, the main data concerning fire source are :

Table 1. Fire size of the gasoline pool fire.

	Case 1	Case 2	Case 3	Case 4
Pool Diameter	2.2 cm	3.5 cm	4.4 cm	5.2 cm
Q_M	0.20 kW	0.51 kW	0.76 kW	1.1 kW
Q_R	350 kW	900 kW	1400 kW	2000 kW

$$\dot{q}_c = \eta \cdot m'' \cdot \Delta h_C \tag{1}$$

$m'' = 0.01667$ [kg/m^{2}s]

$\Delta h_C = 43.7$ [MJ/kg]

$\eta = 0.73$

Combustion efficiency is suggested to be 0.73 and estimated heat release rate is shown in Table 3.[5]

2.3 Scaling Law

The Froude scaling is used to scale model result for comparison with larger scale tests. The scaling method yields the following relationships for velocity and heat release rate.[6]

$$u_F = u_M\left(\frac{L_F}{L_M}\right)^{1/2} \tag{2}$$

$$Q_F = Q_M\left(\frac{L_F}{L_M}\right)^{5/2} \tag{3}$$

Full scale tunnel with 8 m height and 180 m length was scaled with the scaling factor(L_M/L_F) 0.05 in the experiment.

2.4 Numerical Analysis

CFD simulation was carried out to compare the experimental results. The commercial CFD package STAR-CD version 3.10A was selected to obtain numerical results. The Calculation was conducted on a grid of 24×18×100 (43200 cells). Finer grids were used near the fire source and solid wall where strong

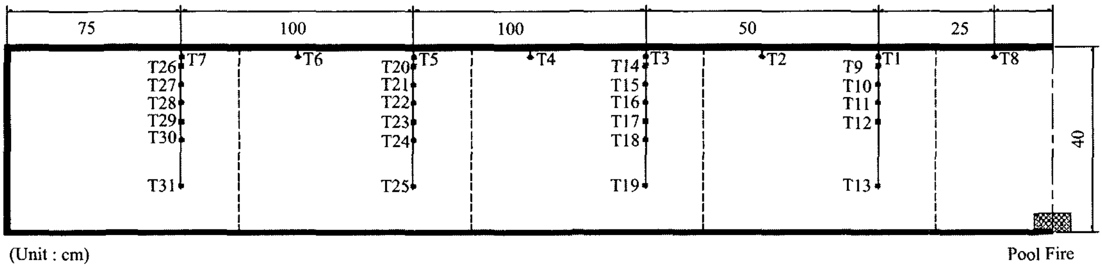

Fig. 1. Schematic of the experimental setup and TC positions.

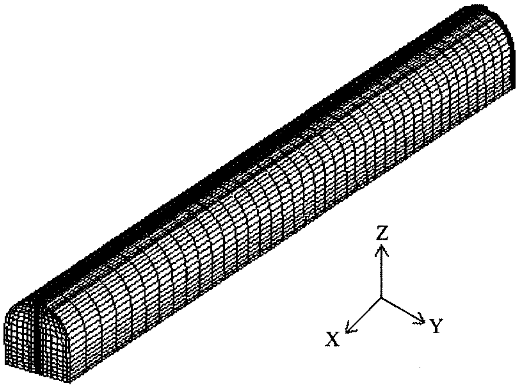

Fig. 2. Grid system of half tunnel.

local gradient of properties were anticipated. Fig. 2 shows the grid system of computational domain.

Fire source is treated as a source of thermal energy with a constant heat release rate for each pool size. Combustion model is not utilized since the interest in the study is on a global impression of the flow field and the smoke distribution. Therefore buoyant plume model was used to describe the fire source.[7]

The flow induced by a fire source is turbulent because the buoyancy force due to the density difference between the hot smoke and the ambient air is much greater than the viscous force. k-ε turbulence model with buoyancy effect was used to simulate the flow generated by fire. Adiabatic wall boundary condition was assumed on all of sides walls except both sides of entrance. Static pressure on the portal boundary was assumed to be zero. The radiative heat transfer was not modeled in this calculation except for the reduction of the experimental heat release rates by 35% due to the radiative heat losses from the fire source.[8]

3. Discussion

3.1 Descent of Smoke Layer

Experimental data were used to verify the results predicted by CFD. In Fig. 3, the measured temperature profile at each station is compared with predicted results for case 1 and 3. Three different station (A), (B) and (C) represent section of horizontal direction 75, 175, 275 cm from the fire source. Without radiation effect in the calculation, the measured temperature is higher than predicted data in the fire region. And another factor of the discrepancy is due to the buoyant plume model describing the fire source. Because the buoyant plume model concerns the plume above the top of the heat addition region in the fire where the flow can be characterized by fluxes of mass, momentum and energy, mean temperature of the fire plume is lower than flame.[9] In the downstream of the fire source, predicted data are in good agreement with measured data because of the reduced radiation effect from the fire source and the energy balance between fire and the buoyant plume. From these temperature profiles, smoke layer dose not come down 50% of tunnel height. The flow field produced by the impingement of a plume on the ceiling of a tunnel spreads out axisymmetrically from the stagnation point to form a ceiling jet. And the development of smoke layer is controlled by the density difference between the ceiling jet and the ambient air, and heat transfer and viscous shear at the wall. Density difference between the hot smoke layer and the ambient air decrease with tunnel length and it grows in thickness of smoke layer below the ceiling. Because of these effects, thickness of smoke layer in short tunnel fire is relatively thin compared to long tunnel. As a result, vertical movement of smoke layer in a short tunnel fire is less important than long tunnel fire. These data will provide useful suggestions for emergency plan with smoke layer development consideration in early stage of fire growth. In this research, horizontal smoke movement is to be more important than downward smoke movement in a short tunnel.

Table 2. Boundary conditions.

	Assumption	
Walls	Adiabatic B.C	$\left(\frac{\partial T}{\partial n}\right)_{wall} = 0$
Portals	Pressure B.C	$p = 0$
Fire source	Buoyant plume model	with 35% radiative loss

3.2 Smoke Layer Propagation

Fig. 4 shows that the velocity of smoke layer varies with the heat release rate. From the experiment, it is found that the velocity of smoke layer is related to heat release rate as follows:

$$U_{sm} = 0.18 \cdot Q^{1/3} \tag{4}$$

This empirical relation for velocity of smoke layer

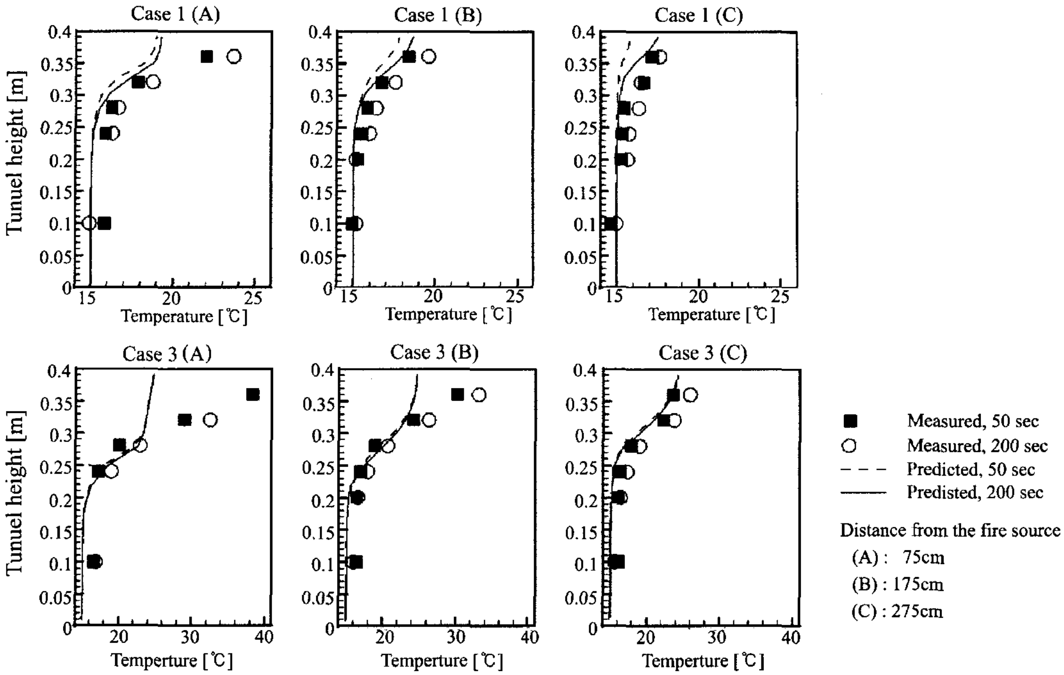

Fig. 3. Temperature profile comparison for case 1 and case 3.

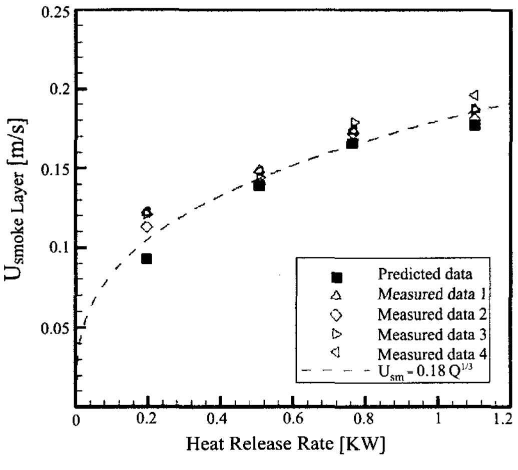

Fig. 4. Velocity of smoke layer with heat release rate.

corresponded well with numerical result, which was proportional to the cube root of heat release rate. This relation by model test was compared with another formula for the front velocity of smoke layer. According to Fannelop, front velocity due to the gravity current which is driven by the temperature difference between the hot smoke layer and the ambient air can be expressed as[10]

$$U_{sm} = 0.67 \cdot \sqrt{gD_h \frac{T_{sm} - T_o}{T_{sm,m}}} \tag{5}$$

$T_{sm,m}$ is the average temperature of the smoke layer between the fire source and the smoke front. This average temperature in the numerical simulation is calculated as follows:[11]

$$T_{sm,m} = \frac{\sum_i T_u \Delta\tau_i}{\sum_i \Delta\tau_i} \tag{6}$$

$\Delta\tau_i$ is a cell volume of the smoke layer.
T_i is temperature of the cell.

The smoke layer interface height was determined by smoke concentration. The minimum smoke concentration of smoke layer is 0.01.[12] Fig. 5 represents average temperature variations of smoke layer at each time. As seen in Fig. 5, temperature of smoke layer was kept constant after approximately 100 sec.

Fig. 6 shows that predicted and measured data converted into the full scale, correspond well with those suggested for front velocity by Fannelop. However

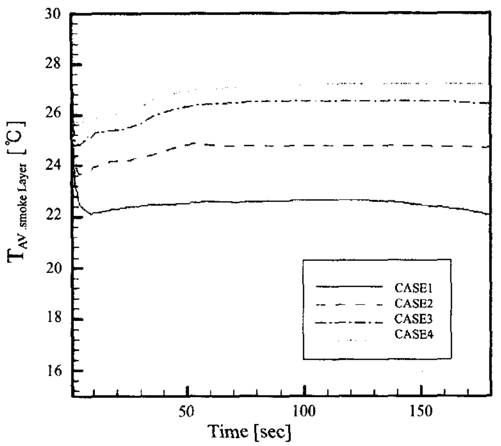

Fig. 5. Average temperature of smoke layer.

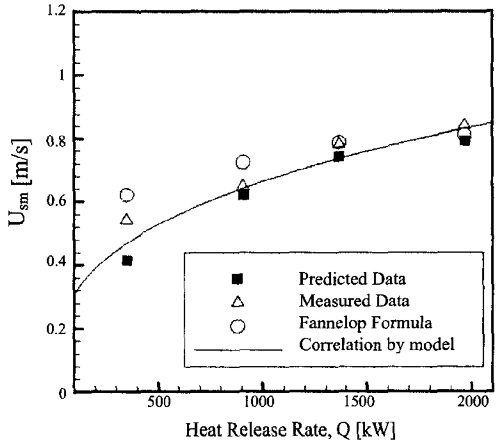

Fig. 6. Comparison of front velocity of smoke layer.

some differences arise in a lower heat release rate region, most of results agrees with each other. In spite of these discrepancies, the average velocity of smoke layer based heat release rate is in better agreement with CFD result than Fannelop formaula using temperature difference.

4. Conclusions

The conclusions for smoke movement are summerized as follows:

(1) Average velocity of smoke layer is proportional to the cube root of heat release rate in both experiments and numerical simulation.

(2) Predicted temperature profiles are in good agreement with that of measured in model tunnel.

(3) Empirical relation based on heat release rate corresponds better with CFD simulation than Fannelop formula by temperature difference.

(4) In a short tunnel fire, Horizontal propagation of smoke layer is more important than vertical smoke movement for evacuation plan.

Notation

D : Pool Diameter, [m]
D_h : Hydraulic diameter [m]
Δh_c : Heat of combustion [MJ/kg]
g : Gravitational acceleration [m/s^2]
L : Tunnel length [m]
m'' : Fuel evaporation rate, [kg/m^{2}s]
T : Temperature [K]
Q : Heat release rate [kW]
q_c : Convective heat release rate [kW]
u : Velocity [m/s]
U_{sm} : Mean Velocity of smoke layer [m/s]

Greek letters

τ : Volume of smoke layer [m^3]
η : Combustion efficiency

Subscript

sm : smoke layer
M : model scale
F : full scale

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