SMOKE CONTROL AND PROPAGATION IN HSUEHSHAN TUNNEL

Falin CHEN[1] and J.C. LEONG[2]

ABSTRACT

Although the 12.9 km Hsuehshan Tunnel has marked the marvelous engineering achievement of Taiwan, its fire safety is an issue demanding serious consideration and planning. In the past few years, serious tunnel fires in Europe have claimed the lives of many victims. A lesson should be learned from these tragedies that deriving proper and efficient ventilation schemes to control the propagation of smoke in Hsuehshan Tunnel is of absolute necessity. In this work, numerical simulations of tunnel fire have been successfully performed using FDS. Based on the numerical results, it was found that the introduction of a dimensionless parameter, called ventilation number in this paper, facilitates the characterization of backlayering effect. Since this parameter has never been discussed elsewhere, this dimensionless parameter needs further justification. Nevertheless, it does currently support a qualitative prediction of backlayering effect. In addition to the ventilation number, a possible form of correlation for the prediction of smoke front velocity is proposed as a function of ventilation velocity and heat release rate of fire source.

Keywords: longitudinally ventilated tunnel, backlayering effect, smoke front velocity.

INTRODUCTION

The need for highly effective transportation system corresponding to high traffic volume has led to the extensive construction of tunnels in areas with either geographical restriction or intensive land use. Since 1990, many tunnels have been built worldwide with individual length hitting the record high. Hsuehshan Tunnel is no doubt a typical example of such tunnels. Hsuehshan Tunnel is the longest in Southeast Asia and the fifth in the world. Although the drilling of its two primary tunnels began in July 1993, the construction of a pilot tunnel for the purpose of geographical survey was actually begun in July 1991. As part of the 31-km Bei-Yi Expressway from Taipei to Yilan, the 12.9-km Hsuehshan Tunnel built through the Hsuehshan is by far the more difficult engineering marvel for the entire project. After nearly 13 years of hard work, the drilling of Hsuehshan tunnel was finally completed in 2004.

In reality, fire accidents rarely take place in tunnels. However, fire safety should be an immense concern for all tunnel users for the potential risk of extremely deadly tunnel fires because the tunnel users and the smoke are partially trapped in the tunnel as compared to a fire in an open space. Although the principle factors influencing tunnel accidents include the tunnel users, the tunnel operators, the vehicles, and the overall infrastructure, most of the fire accidents investigated indicate that the principle causes for most of the tunnel fire accidents are human deficiency and poor maintenance of vehicles. Unlike an open field, the victims trapped in the tunnel are confined within an enclosure where openings are very few. Tragedies can happen not only because of the inhalation of smoke containing toxic and hot gases but also due to the intense radiative heat wave or direct contact with the extremely hot air spreading from the fire source. Thick smoke can result in severe reduction in vision for the tunnel users during evacuation and at the same time cause suffocation and poisoning to its inhalers. Besides, the inhalation of hot gases can be deadly as the respiratory system of the inhaler may collapse within seconds. The increasing length of tunnel built nowadays further puts the tunnel users under higher risks by increasing the chance the users exposed to the hazardous smoke as the users and smoke take longer time to fleet to open spaces. To reduce

1. Professor, Institute of Applied Mechanics, National Taiwan University, e-mail: falin@gauss.iam.ntu.edu.tw
2. Assistant Professor, Department of Vehicle Engineering, National Pingtung University of Science and Technology, e-mail:jcleong@mail.npust.edu.tw

the chance of accidents, tight traffic policy must be enforced within these tunnels. In additional to the law, the design and construction of the tunnels must be extensively justified whereas maintenance and fire drills should be performed on a regular basis. With these measures the loss of lives and properties can be minimized if fires ever break out in the tunnels.

Before 1980's, the safety of tunnel usage was not given too much attention. Because of the rapid increase in the number of recent tunnels built all over the world, tunnel safety has become an important issue inspiring numerous research studies and investigations. A series of recent tragedies happened in European tunnels have shocked the public and awakened all related sectors of the importance of tunnel safety.

The heated air, smoke, and toxic gases generated by a tunnel fire can cause a definite hazard to the tunnel users. A good physical insight in the early stage of tunnel design as well as the maintenance of tunnels to understand the fire dynamics in the tunnel is thus necessary for systematic planning of fire safety measures. Quantitative as well as qualitative knowledge about the detailed behavior of the heated air flow in a ventilated tunnel is required for detection, control, and extinguish. Extensive studies have been conducted on the tunnel fires for the past few decades. These studies consist of theoretical modeling, experimental measurements, and computational simulations. Theoretical modeling of fire and smoke flow presents a challenge for researchers and engineers. Not only are the underlying physical processes difficult to model, but also variables such as the location of the fire source, the geometric space, and the ventilation air flow further complicate the overall behavior of the heated air flow. In general, the smoke flow is simplified in the theoretical approach so that the modeling of gravity current is applicable. Experimental studies are divided into the reduced-scale study performed based on Froude scaling and the full-scale study performed on disused tunnels. Although the earliest full-scale test was carried out as early as 1965, its documentation is hardy accessible. In contrast, full-scale tests recently performed at the Memorial Tunnel in USA (Giblin, 1997), the Repparfjord Tunnel, and the Runehamar Tunnel in Norway (Lemaire, 2003) are more well-known and more frequently referred. In addition to the above, a full-scale testing facility is also available at the Health and Safety Laboratory in Buxton, UK. As one of the recently developed scientific approach, computation approach focuses on the application of field models, in which general flow equations expressing the balance of mass, momentum, and energy are solved simultaneously. Extensive computation was more affordable nowadays thanks to the rapid development of computer hardware and software. In general, most of the studies in this area make use of the Field Model Approach (FMA) that makes use of CFD packages such as JASMINE, CFX, SMARTFIRE, and FDS.

Validated 3D CFD simulations provide an excellent means for visualizing the flow structures of tunnel fires and predicting the tunnel user evacuation. With a powerful post-processor, most CFD codes currently available are capable of creating animation offering better insight of all details of a tunnel fire and smoke flow. Nevertheless, CFD simulations are still restricted by computational time and power readily spent for calculation. Before mid-1980s, the scope of the tunnel fire problems solved was confined to rather simplified ones because of the limitations in computer power. One of the earliest numerical studies of phenomena observed in tunnel fires was performed by Hwang et al. (1977) when CFD approach was promptly introduced. They developed a simple 2D flow model based on the control volume approach to study the development of backlayering effect under the influence of different fire sizes and ventilation speeds. Markatos et al. (1982) also developed a 2D model to study the buoyancy-induced smoke flow in which the fire was approximated as a source of heat and smoke.

With the unprecedented rapid grow of powerful computer resources since mid-1980s, computer power has become more powerful and widely affordable. Consequently, FMA has since then been playing a much more important leading role in the computational study of fires. The first rather complete and successful study was performed by Kumar and Cox (1998) using JASMINE to analyze the steady-state flow in tunnel fires. Other researches include those by Kotoh and Yamanaka (1991), Xue et al. (1993, 1994, 1995, 2001), Woodburn and Britter (1996a, 1996b), Tabarra et al. (1996), Tuovinen et al. (1996), Wu and Bakar (2000), Chen (2000), and Hwang and Edwards (2005).

FORMULATION

The simulations of tunnel fires in this study were performed using Fire Dynamics Simulator (FDS) Version 4, a CFD software developed by the National Institute of Standards and Technology (NIST) to study fundamental

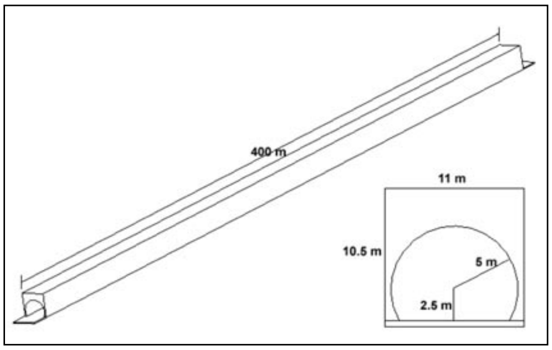


Figure 1. Dimensions of the tunnel considered.

fire dynamics and combustion of fire-driven fluid flow. This CFD package is very useful in the study of residential and industrial fire reconstructions as well as the modeling of smoke handling systems and even the inclusion of detectors and sprinklers. To the knowledge of the authors, there are many studies related to compartment and outdoor fires using FDS but no simulations of fire and smoke movements from tunnel fires until a recent publication by Hwang and Edwards (2005).

Problem Statements

In the discussion that follows, a vehicular tunnel is considered. It is a single-bore unidirectional tunnel of a shape consists of a major arc and a chord of a 5-meter diameter circle. Most tunnels in Taiwan use this geometrical configuration although the diameter of the circle varies. The shape and dimensions of the tunnels is shown in Fig. 1. The tunnel is 400 m in length, 7.5 m in height, and 10 m in width. In this study, the tunnel is assumed only longitudinally ventilated because this ventilation mechanism is most common in Taiwan. In reality, the geometry of a tunnel in use can be much more complicated as different devices are installed in the tunnel. In an actual tunnel, several boosters may be installed along the tunnel to maintain the ventilation. Generally, the installation of boosters is about 200 m apart. In this discussion, it is assumed that an injector is located outside of the left portal of the tunnel providing sufficient ventilation throughout the entire tunnel. This allows us to understand the basic flow patterns without any influences of other secondary factors.

A 2 m x 1 m x 1 m stationary fire source, which is allowed to burn freely with no restriction of air supply in the tunnel, is centrally placed on the base of tunnel. Fresh air enters the tunnel from one portal and leaves via the other end. The walls, floor, and ceiling are considered materials of thermally-thick, a term used in FDS to simulate materials whose surface temperatures are estimated using a one-dimensional heat transfer modeling within the solid materials (McGrattan, 2003). Along the 12.9 km Hsuehshan Tunnel, there are altogether three vertical shaft stations. Each station is installed with two vertical shafts 50 m apart. One of these two shafts is for intake of fresh air while the other is for removal of exhaust air. Since the vertical shaft stations are few, the tunnel considered in this work is expected to be somewhat similar to a section in the Hsuehshan Tunnel significantly far enough from the vertical shaft stations.

Hydrodynamic Model

The simulation of the flows of fresh air from the tunnel portal and hot air from the fire source is based on the schematic shown in Fig. 1. The fire plume emitted from the fire source is a three-dimensional transient buoyant flow suitably modeled using the model Rehm and Baum (1978) developed for a thermally expandable ideal gas. The conservation equations being solved for such a thermally driven low-Mach-number fluid are

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho\mathbf{U})=0 \quad (1)$$

$$\rho\left[\frac{\partial \mathbf{U}}{\partial t}+(\mathbf{U}\cdot\nabla)\mathbf{U}\right]+\nabla p=\rho\boldsymbol{g}+\boldsymbol{f}+\nabla\cdot\boldsymbol{\tau} \quad (2)$$

$$C_p\left[\frac{\partial}{\partial t}(\rho T)+\nabla\cdot(\rho T\mathbf{U})\right]-\frac{Dp}{Dt}=\dot{q}'''+\nabla\cdot k\nabla T-\nabla\cdot\boldsymbol{q}^R+\sum\nabla\cdot h_i\rho D_i\nabla Y_i \quad (3)$$

$$\frac{\partial}{\partial t}(\rho Y_i)+\nabla\cdot\rho Y_i\mathbf{U}=\nabla\cdot\rho D_i\nabla Y_i+\dot{m}_i''' \quad (4)$$

considered constant in the above formulation. The equation of state is required to supplement equations (1) to (4). To simplify the equation of state, according to the technique by Rehm and Baum (1978), the pressure term appears in the formulation is split into the background pressure p0, the hydrostatic pressure $\rho_\infty g z$ and the flow-induced perturbation pressure $\tilde{p}$

In most applications, the background pressure is generally a constant. Although the hydrostatic and perturbation pressures are not constant, they are relatively small in magnitude when compared with the background pressure. Take a tunnel for an example, the background pressure in the tunnel is basically a function of time. The effect of elevation in a tunnel is negligible especially when the slope of a tunnel is assumed small. By replacing the pressure terms in equations (2) and

(3) with $P_{0(t)}$, the flow is assumed weakly compressible with low Mach numbers. This assumption is justifiable for flows in tunnel fires. It is then given as

$$p_0(t) = \rho RT \sum \frac{Y_i}{M_i} = \frac{\rho RT}{M} \quad (5)$$

Large eddy simulation technique

The equations presented above can be solved directly to obtain a solution to the problem of a buoyant fire plume. The difficulty arises in that the length and time scales associated with the fluid dynamics and combustion vary over orders of magnitude. In order to calculate the dynamics of the problem, models for τ and q''' are necessary. The goal is to capture mixing on scales where the eddy viscosity is significant - which generally requires a very fine grid to resolve. Alternative approaches include the use of Reynolds-averaged form of the governing equations or the use of a sub-grid scale description.

The application of the large eddy simulation (LES) techniques to fire is aimed at extracting greater temporal and spatial fidelity from simulations of fire performed on the more finely meshed grids allowed by modem fast computers. The basic idea behind this technique is that the large scale eddies of a large Reynolds number flow are numerically calculated with reasonable accuracy from the governing equations of fluid dynamics. On the other hand, the small scale eddies is modeled using subgrid scales (SGS) description. This work employs the earliest and best-known SGS closure Smagorinsky (1963) has proposed. This model relates the SGS Reynolds stresses to fluid strains through an eddy viscosity coefficient as

$$\tau_{ij} = -2\bar{\rho}\left(C_S\Delta\right)^2 \left|\bar{S}\right| \bar{S}_{ij} \quad (6)$$

where Cs is the Smagorinsky constant and Δ is sometimes referred to as the cutoff length. With this definition, eddies whose sizes are greater than Δ are large scale eddies while those smaller than Δ are small scale eddies. In this study, a value of 0.14 was used for the Smagorinsky constant Cs because this value has produced satisfactory results for most large-scale applications where the effect of boundary layers is insignificant (McGrattan, 1998). The other two variables are defined as

$$\left|\bar{S}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \quad (7)$$

WHEN $$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \quad (8)$$

Combustion model

FDS employs a mixture fraction-based combustion model based on the assumption that large scale convective and radiative transport phenomena can be simulated directly, but physical processes occurring at small time and length scales can only be approximated. When considering the combustion process in a flow field, it is apparent that the time scale is much shorter for the combustion process than the convective process. It is in this case acceptable to assume that the chemical reaction takes place at an infinite reaction rate. Under this assumption, fuel and oxygen can never coexist at a given space and time as fuel and oxygen react instantaneously at any temperature. With this understanding, a single scalar parameter, the mixture fraction Z(x,t), will serve the purpose of representing the local concentration of fuel as well as oxygen. The mixture fraction is a single conserved scalar quantity defined as the fraction of fluid mass at a given point in the flow field that originates as fuel. The mass fractions of all other major reactants and products can be derived from the mixture fraction by means of semi-empirical state relations. These state relations are obtained via combinations of simplified analysis and measurement. The form of the state relation that emerges from classical laminar diffusion flame theory is a piecewise linear function. This leads to a "flame sheet" model Floyd et al. (2003) developed.

Boundary Condition

No-slip boundary conditions are applied at the ceiling, the wall, and the floor of the tunnel. The computational domain extends beyond the tunnel interior in all three directions. All solid boundaries are considered thermally thick. As shown in Fig. 1, the portals of the tunnel are extended to allow fresh air to enter and smoke to exit the tunnel. The fire source (2 m x 1 m x 1 m) is located 100 m downstream of the tunnel entrance. Since fire is simulated via a sub-grid thermal element model (TEM) where a large number of Lagrangian particles are ejected from the burning surface into the plume, releasing heat as they are convected by the thermally induced motion (McGrattan et al., 1998). This process releases an amount of heat energy at a prescribed heat release rate. In this study, heptane was used for the combustion process. As far as the thermal elements are concerned, they are introduced into the computational domain at a velocity calculated from the heat release rate flux, the density of the fuel gases ρ, and the heat of combustion of fuel ΔHc.

$$w_n = \frac{\dot{q}_f''}{\rho_f \Delta Hc} \qquad (9)$$

On the left, a mass flow rate is prescribed whereas on the right, an open boundary condition is assumed.

Numerical Approach

In FDS solver, the spatial derivatives in the governing equations are discretized using second-order central differencing. It also uses a second-order Runge-Kutta scheme to advance the velocity and temperature fields. The linear algebraic system obtained from discretizing the Poisson equation can be solved to machine accuracy by non-iterative methods that apply fast Fourier transform and block tri-diagonal solvers. The rectangular grid is uniformly spaced in the vertical direction but is slight stretched in the horizontal directions. The grid distribution is finer close to the fire source and coarser far away.

RESULTS AND DISCUSSIONS

A numerical simulation of tunnel fire has been successfully performed using FDS version 4. A mesh size of approximately 400,000 grids was used to study the tunnel shown in Fig. 1. Since FDS is developed to study fire situations in buildings, it is not optimized to conform irregular geometries. To build the major arc of the circle outlining the wall and ceiling of the tunnel, a large number of rectangular blocks with appropriate proportions were constructed before they were carefully stacked as multiple layers to construct an approximate surface to represent the actual curved surface. This process is sometimes referred to “stair stepping”. In reality, the sharp corners associated with “stair stepping” will change the flow pattern in their vicinities by introducing unrealistic vorticities. Taking this fact under consideration, FDS provides the prescription of SAWTOOTH, a built-in option, with which the effects due to the generation of vorticities can be lessened.

Smoke Flows

Figure 2 schematically depicts a typical scenario of smoke propagation from a fire source in a tunnel with ventilation flow moving from left to right. The smoke generated from the fire source either propagates upstream against the ventilation flow forming a backlayer or travels downstream along with the ventilation flow. Under some circumstances, the smoke layers both upstream and downstream are well stratified.

In the upstream region, the ventilation flow serves as a counter-flow to the smoke flow reducing the spreading rate of the smoke in the upstream direction. If the inertia force of the ventilation flow is sufficiently greater than that of the smoke flow, no smoke flow is strong enough to propagate against the ventilation current. On the other hand, if the inertia force of the ventilation flow is not sufficiently large enough, a backlayer is always present. This phenomenon is technically referred to as the backlayering effect. In the upstream zone where backlayering effect exists, the flow consists of two distinctive layers, i.e., a hot smoke layer directly under the ceiling and a cold fresh air layer beneath it. These two layers move in opposite directions causing a strong shear at their interface and therefore lead to excessive mixing of hot smoke and cold fresh air.

In the vicinity of fire, the flow is violently turbulent. While the smoke and hot air plume rise naturally due to buoyancy, the ventilation flow pushes the plume to the downstream direction. The tilt angle of fire is not much an important topic as far as the fire safety of tunnel is concerned. Even so, it is still a topic studied and talked about occasionally.

On the other hand, as shown in Fig. 2, ventilation flow at downstream behaves as an aiding flow to the smoke flow because smoke propagates along with the ventilation flow. The rate of smoke propagation in this portion of the tunnel remains generally unchanged. Evidently shown in the figure, the downstream distance the smoke travels increases linearly with time. Depending on the ventilation flow velocity, the smoke may either mix with the fresh air or form a stratified layer above the fresh air.

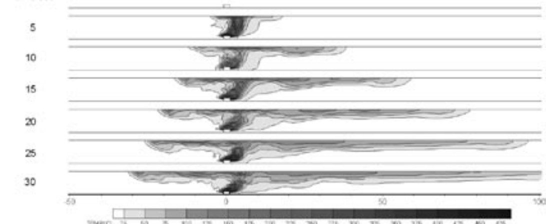


Figure 2. Upstream and downstream smoke propagation when V = 1 m/s and Q = 20 MW.

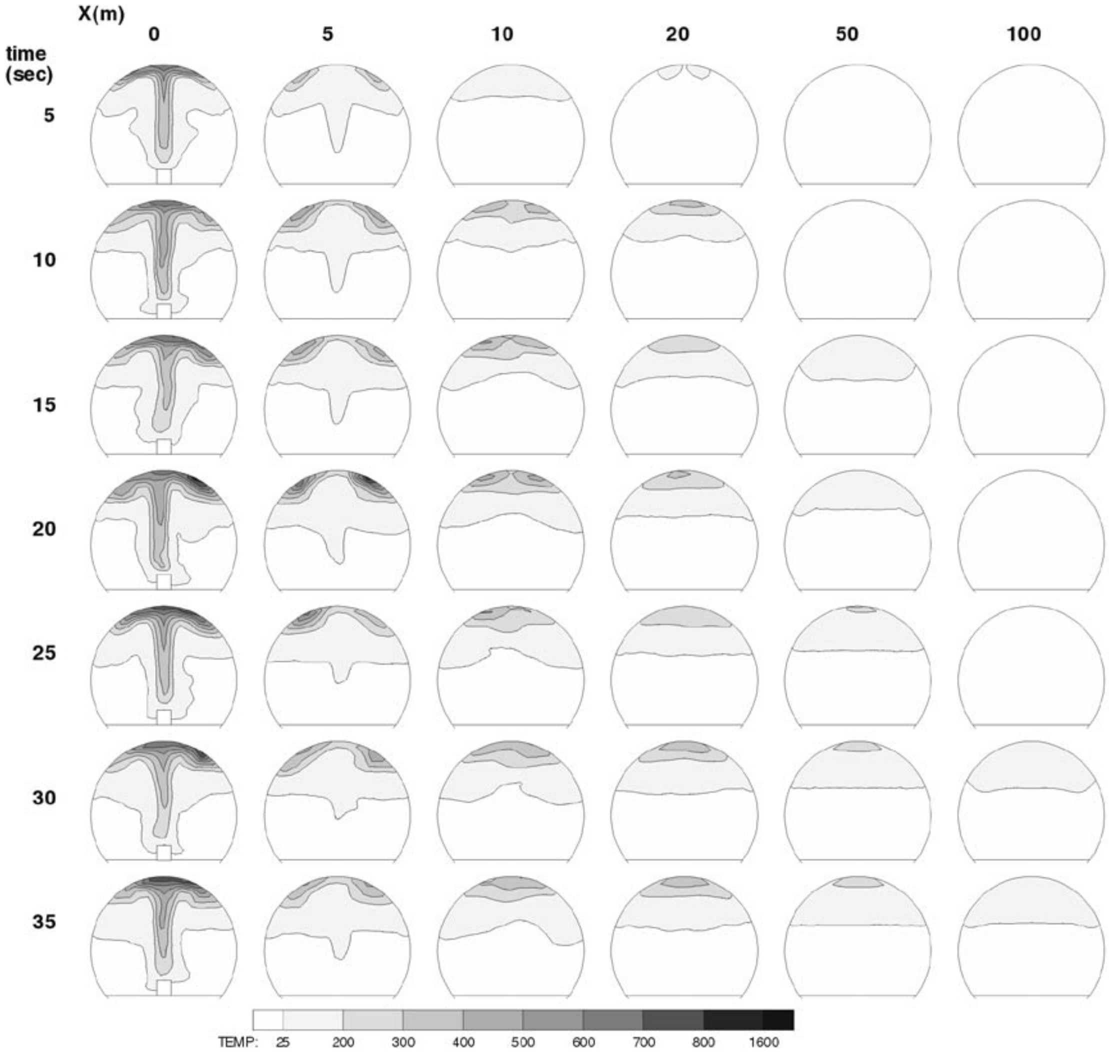


Figure 3. The development of hot smoke stratification at different locations downstream of a 20 MW fire source with a ventilation speed of 1 m/s.

The temperature distribution in the tunnel downstream of the fire source is plotted in Fig. 3 at different time. When X = 0 m, the presence of thermal plume can be clearly observed. At the beginning (t = 5 sec.), the temperature fields at different downstream locations are symmetrical about the central plane of the tunnel. Later (t = 10 sec), non-symmetrical disturbance takes place above the fire source. At this time, temperature fields downstream far away from the fire source remain symmetrical. As time increases, it is apparent that the effect of non-symmetrical disturbance intensifies at X = 0 m and gradually propagates downstream. Thermal stratification is identified at downstream cross-sections shown in Fig. 3. For this case, thermal stratification is generally ensured for locations more than 20 m downstream of the fire source.

Backlayering Effect

The presence of backlayering effect is extremely critical to the tunnel users in the occurrence of tunnel fires. If a fire breaks out in a tunnel, an upward ceiling jet emitted from the fire source impinges towards the ceiling above it due to strong thermal buoyancy. In the course of burning, incomplete combustion produces a large amount of dense smoke right at the spot. The dense smoke would spread and leave the tunnel in both upstream and downstream directions through the opening at the portals. In the event of tunnel fire, ventilation is always provided in the same direction with the traffic direction. Hence, the smoke layer propagating in opposite of the traffic direction is located upstream of the fire source and is named the backlayer. With ventilation, this backlayer is shorter and thicker than the downstream smoke layer due to ventilation as well as the piston effect as cars in front of the fire source leaving the tunnel. In this work the piston effect is not considered as there is no car traveling in the tunnel when fire breaks out.

Because of stratification, Kunsch (1999) suggested that it is reasonable to approximate smoke layers as one dimensional. As far as the flow patterns of the backlayer are concerned, its shape is similar to an inverse gravity current. Since the smoke density is significantly lower than the ambient air due to its higher temperature, the smoke and hot air always travel right below the ceiling. As it is leaving the tunnel, it pushes the ambient air downward clearing itself a path to squeeze through. For this reason, the backlayer is similar to a gravity current in the sense that it consists of two apparent parts, the current front and its tail. The current front is formed as a result of the smoke and hot air layer push their way through the ambient air and their thickness slightly build up as they experience drag exerted by their ambient.

At the current front, the application of Newton's second law perfectly explains the phenomena observed for the propagation of backlayer. There are several important forces imposing significant influence of the flow patterns. These forces include the thermal buoyancy force originated from the fire source, the inertia force provoked by the ventilation, the drag and shear forces exerted by the ambient as relative motion takes place. Among these forces, the thermal buoyancy force is always in the opposite direction with the other three forces in the zone upstream of the fire source. At the downstream zone, the thermal buoyancy and inertia forces are always collateral but the directions of drag and shear depend on the difference in downstream smoke propagation speed and the ventilation velocity. When the downstream smoke propagation speed is greater than the ventilation velocity, slight compression is felt at the front of the downstream smoke layer. In this situation, the drag and shear are in opposite direction with the direction the smoke travels and tend to slow down the smoke velocity. On the other hand, if the ventilation velocity is greater than the downstream smoke propagation speed, drag force disappears and shear acts in the same direction with the ventilation velocity. It pulls the smoke layer with it and eventually enhances the propagation of smoke (Chen, 2000).

Ventilation Number

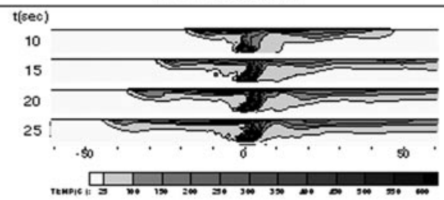
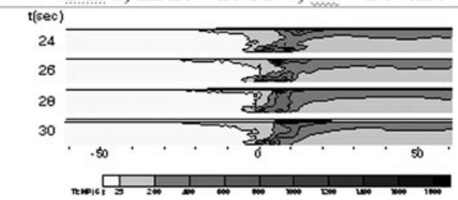
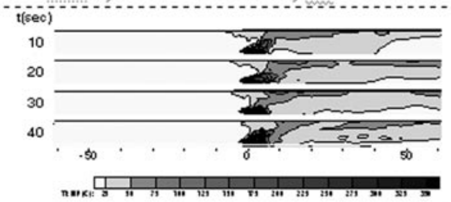
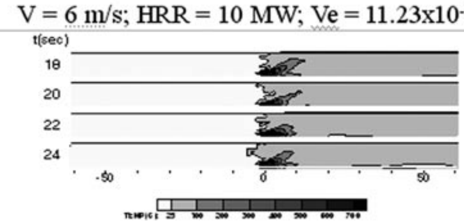
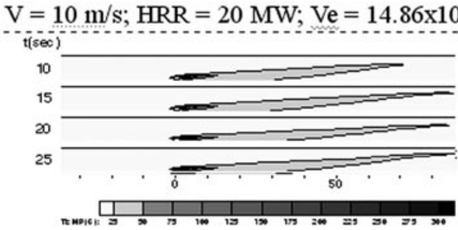
One of the greatest safety concerns related to the design and operation of a tunnel is the critical ventilation velocity. In a typical tunnel fire scenario, smoke rises from the spot of fire, reaches the tunnel ceiling, and flows along the tunnel until it escapes from the confined space of the tunnel. When this happens, ventilation is always introduced to control the spreading of smoke generated. The goal of ventilation is to blow fresh air into the tunnel from the upstream of the fire source so that the smoke and toxic gases produced will only exit the tunnel from the other end of the tunnel. This provides the tunnel users a safe route for evacuation. To ensure the clear route, a ventilation blower system is always used for blowing fresh air into the tunnel, forcing the smoke to flow in the same direction. By definition, the critical velocity is the ventilation velocity at which upstream movement of combustion products, i.e., the backlayering effect, in a tunnel fire is prevented. Unfortunately, there does not exist a universal ventilation speed for all fire scenarios. It is possible that the ventilation air is too weak to force the smoke to exit in the other exit. At this time, backlayer may occur depending on the fire size. It is the desire of all researchers to better understand and to have better control over the presence of backlayer.

In this study, two of the most important factors governing the behaviors of backlayering effect are the heat release rate of the fire and the ventilation velocity. The effects of these two factors are totally opposite to each other. Backlayering effect prevails only when the heat release rate is large or the ventilation velocity is small. To better correlate these parameters with the phenomena, a dimensionless parameter hereby referred as the ventilation number is introduced

$$Ve = \frac{V_{vent}}{\left(Q / \rho \bar{H}^2\right)^{1/3}} \tag{9}$$

where Vvent is the ventilation speed in m/s, Q the fire heat release rate in W, ρ the air density in kg/m3, and A^2 the dynamic height of the tunnel in m. The dynamic height (= 4A / P) is defined as four times the ratio of cross-sectional area to perimeter. This newly introduced ventilation number represents the ratio of

Table 1. Characterization of backlayering effect based on ventilation number.

	Ve	Regimes	Remarks	Flow Patterns
(a)	small	backlayering	Advancing backlayer	 V = 2 m/s; HRR = 20 MW; Ve = 2.97×10^{-2}
(b)			Quasi-steady backlayer	 V = 7 m/s; HRR = 100 MW; Ve = 6.08×10^{-2}
(c)		transition	Slight backlayer	 V = 6 m/s; HRR = 10 MW; Ve = 11.23×10^{-2}
(d)			Vertical plume	 V = 10 m/s; HRR = 20 MW; Ve = 14.86×10^{-2}
(e)	large	No backlayering	Titled plume	 V = 10 m/s; HRR = 1 MW; Ve = 40.33×10^{-2}

the strength of the ventilation velocity to the strength of the buoyancy-induced velocity. In other words, it signifies the relative importance between ventilation effects to the fire source effects. When the flow field in the tunnel is only produced by the fire as the ventilation system is shut down, Ve reduces to zero. In contrast, if the ventilation is much stronger than the fire Ve is large. Under regular situations when fire is absent, the value of Ve corresponds to infinity.

Its values are graphically illustrated in Fig. 4. Apparently, Ve reaches its localized maximum value when fire heat release rate is locally minimal while the ventilation velocity is locally maximal. The range of Ve can be divided into three major regions based on the flow structure as far as backlayering effect is concerned. Two of these regions correspond to the situations where the backlayering effect is either obviously present or confidently absent. In between, there exists a transitional region. These regions are clearly labeled in Fig. 4 as Backlayering (Ve < 6x10-2), Transition (6x10-2 < Ve

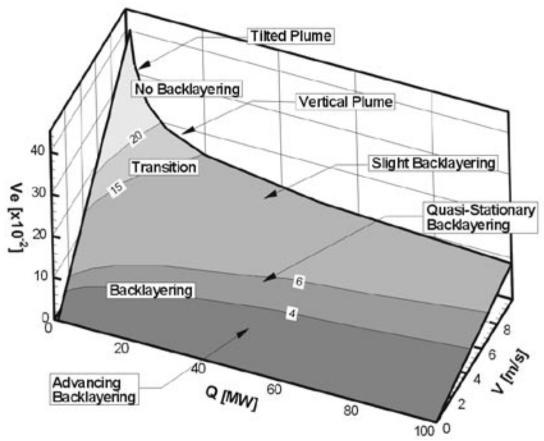


Figure 4. Ventilation number and its corresponding backlayering phenomena.

< 2x10-3), and No Backlayering (Ve > 2x10-3). It is important to point out that the values suggested in the parentheses serve as general guidelines as an absolute differentiation of flow structures is impossible. It is remarkable to point out that the readers should regard these values rather loosely and should not draw any absolute conclusions if the value of Ve is close to either 6x10-2 or 2x10-3. Instead, Ve should be regarded qualitatively in this stage for this newly introduced parameter requires further justification and validation.

Within the Backlayering region, the backlayer can either advancing or quasi-stationary. When Ve is small enough, the buoyancy force is strong enough that the net force at the upstream smoke layer is in the opposite direction of the ventilation. As a result, the backlayering gains enough momentum to move upstream and eventually exits the upstream portal. As shown in Table 1(a), the backlayer expands in the upstream direction at a constant rate. As the ventilation effect increases, i.e., Ve increases, there exists a balance between the inertia and buoyancy forces. If this is the case, it is found that the length of the backlayer is oscillatory. Take the case of V = 7 m/s and Q = 100 MW for an example. The oscillating backlayer is fully developed approximately 6 sec. after ignition. From this time onward, the length of the backlayer fluctuates non-periodically.

If the ventilation effect is further enhanced, the flow regime will go through a transitional stage in which the backlayering effect is significantly suppressed and the presence of backlayer is hardly observed. An example of this flow structure is shown in Table 1(c). With a slight increase in Ve, it is observed that the backlayer will completely disappear. In this case, the smoke rises from the fire source vertically until it reaches the ceiling and then makes a sharp turn flowing longitudinally in the direction of ventilation. If the value of Ve is further increased, the ventilation effect becomes much more dominant than the buoyancy effect. This typically happens when the fire source is very weak under strong ventilation. Because of the much greater inertia effect, the smoke is pushed tilted to the downstream side. The length of the backlayer is very short. In some cases, the diffusion of smoke under the strong ventilation is so effective that the smoke is unable to reach the ceiling. On the other hand, the smoke will stick to the ground and spread for a relatively short distance before it rises. Table 1(e) shows a clear example of this flow structure.

Smoke Front Velocity

In the absence of ventilation, the smoke plume arising from the fire source in a tunnel would continue flowing upwards until it reaches the tunnel ceiling. Once it reaches the ceiling, the ceiling blocks its motion and causes the smoke to flow radially outward. Due to the curvature of the ceiling, the smoke is less likely to travel in the transverse direction. Instead, it is more likely to flow in the longitudinal direction and therefore changes from a radial flow to a one-dimensional axial channel flow, as Mulholland (1995) has described. In this case, both the smoke fronts upstream and downstream are pushed towards the portals at the same speed with equal buoyancy force. This smoke end velocity without ventilation is known as the natural smoke velocity.

By knowing how fast the smoke propagates, its speed can be directly compared with and tied to the ventilation speed. Based on the observations made on CFD results, the natural smoke velocity can be roughly estimated for the tunnel using the following correlation

$$V^0_{smoke}(Q) = 1.0616\,Q^{0.3313} \qquad (10)$$

where V^0_{SMOKE} is the natural smoke velocity in m/s and Q is the heat release rate of the fire source in MW. It is remarkable to point out that the smoke spreads as 1/3 power of the fire heat release rate. The correlation proposed here fits the computational data excellently with an R2-value of 0.9956. While natural smoke velocity has been excellently correlated, this correlation is only useful for considering a tunnel fire that takes place in an old tunnel where mechanical ventilation system is either not installed or out of service. This

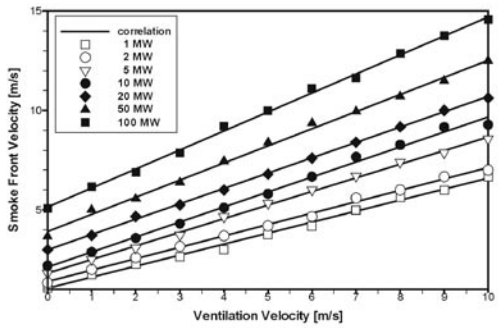


Figure 5. Linear variation of downstream smoke end velocity with respect to ventilation velocity.

scenario is extremely rare nowadays. In reality, ventilation is always applied to control the smoke flow. It has long been documented that the downstream smoke front velocity is always linearly proportional to ventilation velocity. In Fig. 5, the smoke front velocity obtained via numerical means is plot for different ventilation velocities and heat release rates from the fire source. The symbols plotted in the figure represent the data obtained through computational simulations using FDS. As the heat release rate of the fire source increases, the rate of increase in smoke front velocity increases as well. Based on the numerical results obtained, it is possible that a suitable form of expression for smoke front velocity can be written as

$$V_{smoke} = V^0_{smoke}(Q) + F(Q)V_{vent} \quad (11)$$

where Vsmoke and Vvent are the smoke front velocity and ventilation velocity in m/s, Q is the heat release rate of the fire source in MW, and F(Q) is a Q-dependent proportionality function. This form of expression can be easily reduced to two limiting cases. If ventilation is absent, the smoke front velocity reduces to the natural smoke velocity. In contrast, if the heat source is absent, the smoke front velocity reduces to zero regardless of the ventilation speed. This is reasonable because smoke is absent without a fire source. Sure enough, the smoke front velocity should be zero as well. The proportionality function can be expressed as

$$F(Q) = 0.548\,Q^{0.1238} \quad (12)$$

This proposed expression for the proportionality function correlates the function excellently with the fire heat release rate as the associated R2-value for (12) is 0.9885. The FDS simulation data and correlation are plotted in Fig. 5. Combining the above equations, the final form of the correlation can be approximated and simplified to reads

$$V_{smoke} \approx Q^{1/3} + 0.5\,Q^{1/8} V_{vent} \quad (13)$$

CONCLUSIONS

A numerical simulation of tunnel fire has been successfully performed using Fire Dynamic Simulator (FDS) version 4. It was found that the introduction of ventilation number facilitates the characterization of backlayering effect. Although this dimensionless parameter needs further justification, it does provide a qualitative approach to predict backlayering effect. When Ve is small, backlayering effect prevails. Conversely, when Ve is large, backalayering effect is suppressed. This study also proposes a possible form of correlation for the prediction of smoke front velocity (as a function of ventilation velocity and heat release rate of fire source).

ACKNOWLEDGEMENTS

The authors would like to gratefully acknowledge the support on this research by the National Science Council of Taiwan, R.O.C., through research grant NSC92-2811-E-002-011.

REFERENCES

* Chen, F.L. (2000), "Smoke Propagation in Road Tunnels," Applied Mechanics Reviews, Vol. 53, No. 8, 207-218.
* Floyd, J.E., McGrattan, K.B., Hostikka, S., and Baum, H.R. (2003), "CFD Fire Simulation Using Mixture Fraction Combustion and Finite Volume Radiative Heat Transfer," Journal of Fire Protection Engineering, Vol. 13, No. 1, 11-36.
* Giblin, K.A. (1997), "The Memorial Tunnel Fire Ventilation Test Program," ASHRAE Journal, Vol. 39, No. 2, 26-30.
* Hwang, C.C., Chaiken, R.F., Singer, J.M., and Chi, D.N.H. (1977), "Reverse Stratified Flow in Duct Fires: A Two-Dimensional Approach," 16th Symposium on Combustion, 1385-1395.

* Hwang, C.C., and Edwards, J.C. (2005), "The Critical Ventilation Velocity in Tunnel Fires – a Computer Simulation," Fire Safety Journal, Vol. 40, 213-233.

* Kotoh, S., and Yamanaka, G. (1991), "Air Flow Analyses in a Longitudinally Ventilated Road Tunnel on a Fire," ASME/JSME Thermal Engineering Proceedings, Vol. 5, 347-354.

* Kumar, S., and Cox, G. (1998), "Radiant Heat and Surface Roughness Effects in the Numerical Modeling of Tunnel Fires," 6th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, BMRA, The Fluid Engineering Centre.

* Kunsch, J.P. (1999), "Critical Velocity and Range of a Fire-Gas Plume in a Ventilated Tunnel," Atmospheric Environment, Vol. 33, No. 1, 13-24.

* Lemaire, T. (2003), "Runehamar Tunnel Fire Tests: Radiation, Fire Spread and Back layering," Proceedings of the International Symposium on Catastrophic Tunnel Fires, 105-116.

* Markatos, N.C., Malin, M.R., and Cox, G. (1982), "Mathematical Modelling of Buoyancy-Induced Smoke Flow in Enclosures," International Journal of Heat and Mass Transfer, Vol. 25, 63-75.

* McGrattan, K.B., Baum, H.R. and Rehm, R.G. (1998), "Large Eddy Simulation of Smoke Movement," Fire Safety Journal, Vol. 30, No. 2, 161-178.

* McGrattan, K.B., Baum, H.R., Rehm, R.G., Forney, G.P., Floyd, J.E., Prasad, K., and Hostikka, S. (2003), Fire Dynamics Simulator (Version 4) - Technical Reference Guide, Technical Report NISTIR 6783, 2003 Edition, National Institute of Standards and Technology, Gaithersburg, Maryland.

* Mulholland, G.W. (1995), "Smoke Production and Properties," SFPE Handbook, National Fire Protection Association, Quincy, Massachusetts, 2nd edition.

* Rehm, R. G. and Baum, H. R. (1978), "The Equations of Motion of Thermally Driven Buoyant Flows," Journal of Research, National Bureau of Standards, Vol. 83, No. 3, 297-308.

* Smagorinsky, J. (1963), "General Circulation Experiments with the Primitive Equations. I. The basic experiment," Monthly Weather Review, Vol. 91, 99-164.

* Tabarra, M., Kenrick, B., and Matthews, R.D. (1996), "CFD Validation of Natural Smoke Movement in a Model Tunnel," Fluids Engineering Division Conference, ASME, Vol. 238, 543-546.

* Tuovinen, H., Holmstedt, G., and Bengtsson, S. (1996), "Sensitivity Calculations of Tunnel Fires Using CFD," Fire and Technology Sec. Qua. 99-119.

* Woodburn, P.J., and Britter, R.E. (1996a), "CFD Simulations of a Tunnel Fire – Part I," Fire Safety Journal, Vol. 26, 35-62.

* Woodburn, P.J., and Britter, R.E. (1996b), "CFD Simulations of a Tunnel Fire – Part II," Fire Safety Journal, Vol. 26, 63-90.

* Wu, Y., and Bakar, M.Z.A. (2000), "Control of Smoke Flow in Tunnel Fires Using Longitudinal Ventilation Systems - a Study of the Critical Velocity," Fire Safety Journal, Vol. 35, No. 4, 363-390.

* Xue, H., Chew, T.C., and Cheong, H.F. (1995), "Transient Three-Dimensional Fire-Induced Airflow in a Full Scale Ventilated Tunnel," Combustion Science and Technology, Vol. 105, 117-129.

* Xue, H., Ho, J.C., and Cheng, Y.M. (2001), "Comparison of Different Combustion Models in Enclosure Fire Simulation," Fire Safety Journal, Vol. 36, No. 1, 37-54.

* Xue, H., Hihara, E., and Saito, T. (1993), "Turbulence Model of Fire-Induced Air Flow in a Ventilated Tunnel," International Journal of Heat and Mass Transfer, Vol. 36, 1739-1748.

* Xue, H., Hihara, E., and Saito, T. (1994), "Temperature Stratification of Heated Air Flow in a Fire Tunnel," JSME International Journal, Series B, Vol. 37, 187-194.