procedure. Published papers can be found regularly in open literatures on this subject [1,12].

A real fire in long tunnels resulting from the burning of a car or a truck is extremely complex and very difficult to simulate. This is because a vehicle consists of many different materials and the burning process involves many complex chemical reactions. In order to reduce greatly the complexities of simulations, the fire is treated as a predetermined heat source in the present study. A finite-difference method, which solves the unsteady, compressible, three-dimensional Navier-Stokes equations and the energy equation, is employed to simulate this physical problem.

Ⅱ. GOVERNING EQUATIONS

The governing equations are the unsteady, compressible, three-dimensional Navier-Stokes equations and the energy equation, they are described as follows.

Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (1)$$

Momentum equations

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=$$
$$-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[\frac{2}{3}\mu\left(2\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}-\frac{\partial w}{\partial z}\right)\right]$$
$$+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]$$
$$-\rho g\sin\theta \quad (2)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=$$
$$-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]$$
$$+\frac{\partial}{\partial y}\left[\frac{2}{3}\mu\left(2\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}-\frac{\partial w}{\partial z}\right)\right]$$
$$+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]-\rho g\cos\theta \quad (3)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=$$
$$-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]$$
$$+\frac{\partial}{\partial z}\left[\frac{2}{3}\mu\left(2\frac{\partial w}{\partial z}-\frac{\partial u}{\partial x}-\frac{\partial v}{\partial y}\right)\right] \quad (4)$$

Energy equation

$$\rho\left(\frac{\partial e}{\partial t}+u\frac{\partial e}{\partial x}+v\frac{\partial e}{\partial y}+w\frac{\partial e}{\partial z}\right)+p\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)$$
$$=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\dot{Q}+\Phi \quad (5)$$

$$\Phi=\mu\left[2\left(\frac{\partial u}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+2\left(\frac{\partial w}{\partial z}\right)^2+\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial y}+\frac{\partial v}{\partial z}\right)^2\right]$$
$$+\mu\left[\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)^2-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)^2\right]$$

Equation of state

$$p=\rho RT \quad (6)$$

In the above equations, $\dot{Q}$ is the energy release rate and Φ is the dissipation function which represents the rate at which mechanical energy is expended in the process of deformation of the fluid due to viscosity. The buoyancy effect due to density change appears in the last term of the x- and y-momentum equations. The parameter θ represents the grade of the tunnel. There is no combustion model used in the present work, therefore, $\dot{Q}$ is the energy release rate of the fire source and is assumed to be a known value through some experimental means. The disturbances caused by a fire are quite strong, the flow certainly is turbulent. The turbulence model used in this study is Prandtl's mixing length model [4]. The viscosity is the sum of laminar viscosity and turbulent viscosity.

$$\mu=\mu_l+\mu_t \quad (7)$$

$$\mu_1 = \rho L^2 \{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2\} \quad (8)$$

In the above equation, L is the mixing length and is chosen to be 1% of the tunnel height [4].

Ⅲ. INITIAL AND BOUNDARY CONDITIONS

The initial temperature and pressure inside the tunnel are assumed to be 27^oC and 101.3 kPa respectively. The non-slip condition is assumed for three velocity components on all walls. The boundary values of *u*, *v*, *w*, and *T* at the exit of the tunnel are obtained by extrapolation. For example, the *u* velocity distribution along the three points next to the exit is approximated by a second-order polynomial, the boundary value is then obtained by extrapolating the polynomial out to the boundary. The pressure at the tunnel exit is fixed at atmospheric pressure, 101.3 kPa.

A convection heat transfer on the wall is assumed for the energy equation, which is described below [8]

$$-k\frac{\partial T}{\partial n} = h(T - T_a) \quad (9)$$

$$h = \begin{cases} h_{\min} & for \quad T = T_\infty \\ h_{\min} + \frac{h_{\max} - h_{\min}}{100}(T - T_\infty) & for \quad T_\infty \le T \le T_\infty + 100 \\ h_{\max} & for \quad T \ge T_\infty + 100 \end{cases} \quad (10)$$

In the above equations, $\partial T/\partial n$ is the normal temperature gradient of air on the wall, T_a is the average temperature of a cross section. The parameter *k* is the thermal conductivity of air. The parameters $h_{\min}$ and $h_{\max}$ are the minimum and maximum heat transfer coefficients of air and their values are $5\ W/m^2\cdot{}^0k$ and $40\ W/m^2\cdot{}^0k$ respectively.

Ⅳ. NUMERICAL PROCEDURES

An explicit finite-difference scheme is used to solve the governing equations. A forward-difference and a central-difference discretizations are employed for the time derivative terms and diffusion terms respectively. The QUICK scheme of Leonard [7] is applied to the nonlinear convection terms. Because of the complexity of the compressible Navier-Stokes equations, it is not possible to obtain a closed-form stability criterion for this explicit scheme. However, the following empirical formula can normally be used [13].

$$\Delta t \le \left(\frac{|u|}{\Delta x} + \frac{|v|}{\Delta y} + \frac{|w|}{\Delta z} + a\sqrt{\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}}\right)^{-1} \quad (11)$$

where a is the speed of sound. The above restriction is due to the inviscid Courant-Friedrichs-Levy (CFL) condition. A second stability requirement is related to the explicit diffusion terms in the momentum and energy equations. Momentum and energy cannot diffuse more than approximately one cell per time step. In the present problem, the time step restriction due to the CFL condition is much more severe than that due to diffusion. Therefore, the CFL condition is used to estimate the allowable time step.

Ⅴ. RESULTS AND DISCUSSIONS

The fluid and thermal behavior of tunnel fires is three-dimensional and transient. Because a three-dimensional simulation is more complex and requires large amount of computer resources, the computer program was first written to simulate two-dimensional fires. The results were validated by experimental data [9]. After that, we then extended the program to three-dimensional simulations.

1. Two-dimensional simulations of natural ventilation

We first simulated a fire two-dimensionally under natural ventilation, there was no mechanically forced airflow imposed. The configuration and dimensions of the tunnel are shown in figures 1.(a) and (b) respectively. The left side of the tunnel was sealed off. The fire source was modeled by burning ethyl alcohol in a pan with an area of 2 m^2. The location of the fire source and locations of velocity and temperature measurements are also shown in figure 1 [9]. The computational domain consists of 575 grids longitudinally and 24 grids vertically.

The energy release rate of the fire source was assumed to increase linearly from the moment of ignition (t=0 second) to t=30 seconds. After that, the rate was assumed to fix at 2 megawatts [4]. Velocity and temperature measurements were taken experimentally 14 minutes after ignition [9]. Figure 2 shows the comparison of calculated vertical temperature distributions with experimental data at three different longitudinal locations. The experimental data were taken on the longitudinal center plane of the tunnel. At 50 meters away from the fire source, the agreement between prediction and experimental data are decent, except at locations near the ceiling. Near the ceiling, the predicted values are lower than experimental data. The possible cause for this discrepancy might be that the tunnel's upper half section is of arch shape, heat tends to accumulate over there. But a two-dimensional simulation implies that the cross section is of rectangular shape, heat reaches the ceiling can diffuse laterally more easily than the arch shape ceiling. The discrepancy continues and enlarges as one moves away from the fire source. Figure 3 shows the comparison of calculated velocities with experimental data at the corresponding locations. The agreement is fair at all three locations, but the trend of velocity profiles was predicted correctly.

2. Two-dimensional simulations of forced ventilation

The second case studied was a fire under forced ventilation. The configuration and dimensions of the tunnel simulated were the same as those of section V.1. The tunnel was longitudinally ventilated and allowed one way traffic only. When a fire broke out, the cars in front of the fire could drive away safely, but the cars behind would be stopped. The ventilation fans were utilized to impose airflow to prevent the fire from propagating backwards. Two ventilation velocities, 2 m/sec and 3.5 m/sec, from left to right were used. The fire source was 5 megawatts, which is approximately equal to the power released by a passenger car on fire.

It was found that if the fire source were placed on the ground (as the test setup), the hot plume from the fire source acted like an upward curtain jet and shut off the longitudinal movement of cold air. However, in a real tunnel the cold air could bypass freely through the sides of the fire source. To simulate this situation, the fire source was placed on the mid-height (only in two-dimensional simulations), leaving free passage for the cold air. Figure 4 shows temperature and velocity fields at five different instants. It can be seen from figure 4 that 2 m/sec was not able to stop the high temperature gas from propagating to the left, but a ventilation velocity of 3.5 m/sec was able to retard it effectively. The people and cars stopped by the fire were therefore protected.

3. Three-dimensional simulations of natural ventilation

In three-dimensional simulations, we simulated an abandoned tunnel with its left side closed and its right side open to atmosphere. Its configuration, dimensions, and locations of measurement are shown in figure 5 [14]. Its length and cross-sectional area are 390 meters and 25 m^2 respectively, it also has an upgrade of 2.18% from left to right. There were several injection fans placed on the ceiling of the left end to impose the airflow required for forced ventilation.

We first simulated a fire under natural ventilation. The fire source was 108 meters away from the left end and was modeled by burning gasoline in a pan with an area of 2.6 m^2 in the experiment [14]. The energy release rate was 14.5 megawatts and was assumed to increase linearly from t=0 second to t=10 seconds [3]. The computational domain consisted of 197 grids longitudinally, 21 grids vertically, and 13 grids laterally. Due to the longitudinal symmetry of the tunnel, the computational domain was only a half of the physical domain.

The predicted temperature and the corresponding experimental data at several different cross sections are compared in table 1. The locations of L and M in the table are 0.5 and 1.8 meters above the ground respectively, and H is 0.5 meters below the ceiling (figure 5). At station 5, which is right at the fire source, the measured temperature at H is much higher than the predicted value. This large discrepancy also occurs at H of station 4, which is located 10 meters to the right of the fire source. But the agreement is better at M and L (lower portion of the tunnel). The agreement gets better at locations further away from the fire source. The large discrepancy between predictions and experimental data at locations very near the fire source had also been reported by other researchers [3, 5].

The observations and experience gained from the numerical experiment suggest the following explanation. In numerical simulations, gasoline is assumed to have completed its combustion process and released its energy right at the surface of the pan (because no combustion model is used in the present study), while in the test, the combustion process may continue up to the ceiling (the ceiling is only 4 meters high). Therefore, some energy will be released very near the ceiling resulting high temperature there. From this point of view, the predicted temperature should be higher than experimental data in the lower region of the tunnel. This is confirmed by the results in table 1 that the predicted temperatures at M and L points at stations 4 and 6 (10 meters to the right and left of the fire source) are higher than experimental data. To resolve this discrepancy, a combustion model is needed to simulate the burning process of the fuel. Nevertheless, in a real tunnel fire, the burning process of a car or a truck is extremely complex, difficult to solve, and very demanding on computer resources. Treating the fire as a heat source and determining its energy release rate by some experimental means is a pragmatic engineering approach in the prediction of tunnel fires.

4. Three-dimensional simulations of forced ventilation

The second case studied in three-dimensional simulations was a fire under forced ventilation. The energy release rate of the fire source was 24.95 megawatts [14]. Three ventilation velocities, 2, 3, and 4m/sec (from left to right), subject to the same fire source, were used. The results of simulations showed that 2 and 3 m/sec are not able to stop the hot gas from propagating to the left, but 4 m/sec is able to retard the hot gas effectively. The people and cars stopped behind the fire are therefore protected. Table 2 shows the comparison of predicted and measured temperatures at several different longitudinal cross sections. The agreement is much better than that of the natural ventilation case. This is because the convection plays an important role under the forced ventilation. The energy released by the fire is transported downstream much faster and therefore temperature is more evenly distributed. Turbulence model may also plays an important role here and a better model may improve the accuracy of the simulations. This, of course, is a future subject to be studied.

The stability constraint is quite severe for the numerical scheme used in the present study as shown in equation (11). This occurs because greatly varying signal speeds (u,v,w and the speed of sound) appear in the governing equations and the traditional solution schemes attempt to honor all of them [13]. It can be seen that the sound speed is the dominant factor for the small time step required. The convergence to a steady state solution is usually slow, or for time-dependent solutions, the allowable time step becomes very small. This difficulty is not due to the physical characteristics but to the mathematical structure of the governing equations. There are several alternatives to overcome this problem [2, 13] and are currently being investigated by the author.

Ⅵ. CONCLUSIONS

A numerical procedure based on the three-dimensional Navier-Stokes equations and the energy equation has been developed to simulate fires in long vehicle tunnels. Both two- and three-dimensional simulations have been conducted. It has been found that simpler two-dimensional simulations are able to give decent qualitative results. Although only a simple mixing length turbulence model was employed, three-dimensional simulations show reasonable agreement with experimental data, except in the region very near the fire source in the case of natural ventilation. A combustion model is needed to resolve this problem. However, a real tunnel fire resulting from the burning of a car or a truck is extremely complex and very difficult to simulate, and also is very demanding on computer resources. The results of the present work suggest that treating the fire as a heat source and releasing its energy at different height (with some physical modeling and validation) is a pragmatic engineering approach and can be an effective tool in the prediction of fires in long vehicle tunnels.

NOMENCLATURE

a	speed of sound, *m/s*
e	internal energy, J/kg
g	gravitational constant, m/s^2
h	convection heat transfer coefficient, $W/m^2\cdot{}^oK$
k	thermal diffusivity of air, $W/m\cdot{}^oK$
L	mixing length, *m*
n	coordinate on the outward normal direction of a surface, *meters*
p	static pressure, N/m^2
$\dot{Q}$	energy release rate of the fire source, J/s
R	gas constant, $m^2/(s^2\cdot{}^oK)$
T	temperature, ${}^oK$
u,v,w	dimensional velocity components, *m/s*
x,y,z	dimensional coordinates, *meters*
Δt	time step, *seconds*
$\Delta x, \Delta y, \Delta z$	grid size on x-, y-, and z-directions,*meters*
Φ	dissipation function, J/s
μ	absolute viscosity, $N\cdot s/m^2$
ρ	density, kg/m^3
θ	grade of the tunnel, *radians*

SUBSCRIPTS

a	average
l	laminar
t	turbulent

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