SMOKE MOVEMENT IN TUNNEL NETWORK

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ABSTRACT

A theoretical model about smoke movement in tunnel network is presented. Field model is adopted in fire origin section and network model in other branches of tunnel network. With the model, fire emergency case in Tehran Subway Line #1 of Iran is analysed. According to the simulation results, reasonable ventilation options are suggested to different fire case.

Keywords: *Tunnel network; Field model; Network model; Fire; Ventilation*

1 INTRODUCTION

The continuously growing of fire damage has drawn attention of the human being. In most cases a fire in a road vehicle in the open can be dealt with by the fire brigade without special difficulty. But that same fire in a tunnel may be a vastly more serious and difficult problem because the heat and toxic combustion products are not rapidly diluted and dissipated as they are in the open air but are contained within the tunnel to form obstacles to escape, rescue and fire-fighting.

With more and more tunnels being built and an ever increasing volume of traffic using them it is becoming increasingly important to build up a quantitative picture of fire behaviour in tunnels and to understand what risks are being run. An understanding of what is likely to happen in the event of fire is essential for the formulation of soundly based plans to counter the effects of fire. On the one hand there is the possibility of limiting the incidence of serious fires by restricting the types and the quantities of flammable materials passing through a tunnel, and on the other, there is the question of how a fire in a tunnel can be dealt with and whether escape and fire-fighting can be assisted, for example, by control of the ventilation. All such considerations apply with even more force to the tunnels of the future whose design should be based on the most up-to-date knowledge.

A fire in tunnel has the effect of throttling the ventilating air flow. This effect is caused by the rapid expansion of the air flowing past the fire site. Also as a consequence of the law of conservation of mass, the velocity of the hot gases downstream of the fire increases inversely proportional to the density (or equivalently, directly proportional to the absolute temperature of the gases), hence increasing the viscous pressure losses in this section of the tunnel. These pressure changes will reduce the tunnel air flow. The density differences between the hot gases and the ambient air give rise to pressure differentials which can either augment or retard the tunnel air flows, depending on the direction of ventilation (uphill or downhill). The elevated air temperatures produced by a fire cause the tunnel walls to heat up, determining the conditions downwind of the fire.

In the tunnel situation we must differentiate between two regions of flame and combustion gases, a region of vertical and a region of horizontal flow. Heat fed back from the flame evaporates liquid fuel and causes decomposition in solid fuel which liberates volatile combustibles. These combustibles rise, mix with air and form a flame. The mixing of air takes place by turbulent entrainment which is a very vigorous process when the flame is rising upwards. The tip of the flame marks the point where combustion of the flammable volatile is largely complete, but the combustion products are still very hot and continue to rise in a plume, entraining more air.

In ordinary buildings, where considerable dilution of the smoke may occur as it passes such barriers as doors, people are occasionally trapped and killed. Very roughly speaking the smoke tends to obscure escape routes and impede escape for people who are then killed by undue exposure to the fire gases. In practice there is a considerable overlap between these two fields of influence, and the irritancy of the smoke may cause distress, make the eyes water and reduce vision irrespective of whether there is optically dense smoke.

Therefore, practicable and precise fire model is specially important for tunnels. Such a model can be used not only allow alternative for testing various fire protection designed strategies, but also as a tool both for training fire fighters and perhaps even eventually for decision making during a fire.

There are several computer models on fire [1]. Empirical modelling combines the empirical formulae and the modern computer technology. Semi-physics modelling combines the empirical formulae and basic mathematical equations derived from the fundamental laws.

Physical modelling, however, is a kind of advanced modelling based on the governing equations of mass, momentum, energy, chemical relation, etc.

Traditional method dealing with tunnel fire is a one-dimensional model, such as SES model (Subway Environment Simulation) [2].

The SES Fire Model has been designed with the ability to simulate the "overall" effects of a tunnel fire on the ventilation system. This level of detail is considered sufficient for evaluating the adequacy of an emergency ventilation system. However, the SES is a one-dimensional model. Therefore, the results of a fire simulation will indicate whether or not the ventilation air flows are sufficient to prevent backlayering, but not the extent of backlayering (a two-dimensional phenomena) if it is predicted to occur. In addition, the early stage of a fire, before the ventilation system is activated, generally cannot be simulated since this period is dominated by buoyant recircultaing two-dimensional air flows.

According to *SUBWAY ENVIRONMENTAL DESIGN HANDBOOK* [3], emergency air velocity must be at least 500 fpm if air motion is also to serve as an indicator for patrons. If it is not, the emergency air velocity can be lower. Li and Yan [4] believe that the ventilation rate should be about 2m/s to prevent hot air from spreading upstream. According to Chinese subway design code [5], emergency air velocity must be at least 2m/s to prevent hot smoke from spreading upstream, which contributes to help patrons evacuating.

In order to improve the ability to deal with fire, a combined model, e.g., F-N (Field-Network) model, is presented and is used to analyse the smoke movement in Tehran Subway Line #1 system.

2 MATHEMATICAL MODEL

In our computer model TNFIRE (Tunnel Network FIRE), three-dimensional field model is used in domain with strong fire origin and strong ventilation while Network Model in other branches (the same as SES has done). Therefore, TNFIRE can predict the early stage of a fire and give more information near fire origin in details.

2.1 Network Model

The governing equations of a network are as following:

$$\mathbf{B}\bullet\mathbf{E}\bullet\frac{d\vec{G}}{dt}=\frac{g}{\rho}\bullet\mathbf{B}\bullet(\vec{DH}-|\mathbf{G}|\mathbf{G}\bullet\vec{S}-\Delta\vec{Z})$$

$$\mathbf{A}\vec{G}=\vec{Q}$$

where **A** is the correlation matrix of network, **B** the basic circuit matrix;

$$\mathbf{E}=\begin{bmatrix} L_1/F_1 & & & 0 \\ & L_2/F_2 & & \\ & & \ddots & \\ 0 & & & L_n/F_n \end{bmatrix}$$

$$\mathbf{G}=\begin{bmatrix} G_1 & & & 0 \\ & G_2 & & \\ & & \ddots & \\ 0 & & & G_n \end{bmatrix}$$

$$\vec{G}=(G_1, G_2, \cdots, G_n)^T \quad \vec{S}=(S_1, S_2, \cdots, S_n)^T \quad \Delta\vec{Z}=(\Delta Z_1, \Delta Z_2, \cdots, \Delta Z_n)^T$$

$$\vec{DH}=(DH_1, DH_2, \cdots, DH_n)^T \quad \vec{Q}=(Q_1, Q_2, \cdots, Q_m)^T$$

g is the gravitational acceleration; ρ is the density of fluid; L_i is the length of branch i; F_i is the cross-section area; G_i is the flow rate; S_i is the resistance coefficient; ΔZ_i is the height difference; DH_i is the pressure head gained; Q_i is net flow rate at node i.

The underground heat transfer /heat sink is calculated based on the eigenvalue method to analyse the unsteady heat transfer problems in underground spaces.

2.2 Field Model

The model is consisted of 3-dimensional, time-dependent continuity, momentum, energy, species equations and turbulent kinetic energy and dissipation rate equations.

All the equations obey the following general partial differential equation:

$$\frac{\partial}{\partial t}(\rho\varphi)+\frac{\partial}{\partial x}(\rho u\varphi)+\frac{\partial}{\partial y}(\rho v\varphi)+\frac{\partial}{\partial z}(\rho w\varphi)=\frac{\partial}{\partial x}(\Gamma_\varphi\frac{\partial\varphi}{\partial x})+\frac{\partial}{\partial x}(\Gamma_\varphi\frac{\partial\varphi}{\partial x})+\frac{\partial}{\partial x}(\Gamma_\varphi\frac{\partial\varphi}{\partial x})+S_\varphi$$

Where ρ, u, v, w, φ, Γ_φ, S_φ are density, x-direction velocity component, y-direction velocity component, z-direction velocity component, general fluid property, effective exchange coefficient of the property φ and source term of property φ respectively. Property φ stands for variable such as u, v, w, T, C, k, ε etc. C stands for the smoke concentration.

Field Model solves 8 time-dependent partial differential equations. Since all these variables are coupled each other, iteration must be done at any time step. Since the general form partial differential equation is intensively non-linear, much CPU time must be spent to get convergence solution.

2.3 Method of Solution

MMKP[6] method is used to solve the equations of network.

SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm[7] is used to solve the above-mentioned partial equations.

The solving procedure is shown in Figure 1.

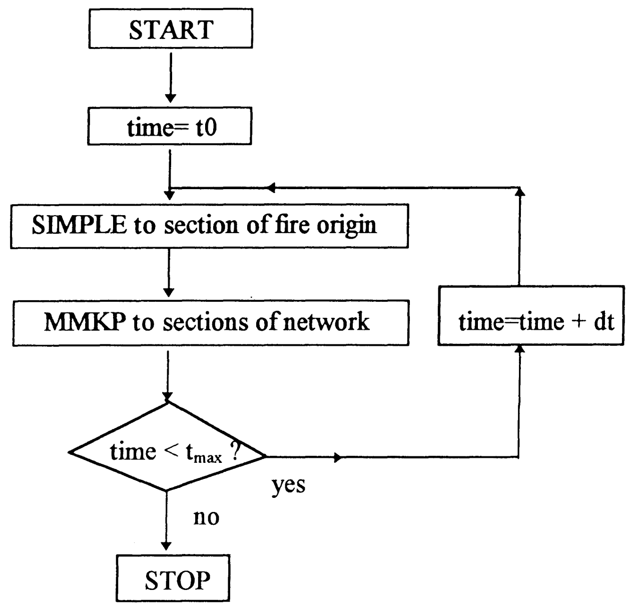

Figure 1 Flow chart for solution algorithm

3 RESULTS AND DISCUSSION

There are 14 stations in Tehran Subway Line #1: E1, F1, G1, H1, ..., Q1 and R1 station. The track slope is quite high (maximum to 5%). From station E1 to R1, train travel upward continuously. The height difference between station R1 and E1 is about 400m. It is a very unfavourable factor in fire emergency because the whole tunnel system will act as a big chimney. Therefore, it is very crucial to control the hot smoke spreading up to the upper station in case of fire emergency.

In order to determine the most reasonable fire emergency operation scheme, a tunnel section between station F1 and G1 is chosen as the study object. This section is at the bottom of line #1. If fire takes place here, there will be a very strong tendency for hot smoke to move upwards to station G1, then H1 and so on due to the pressure caused by the density difference between air and smoke. To make it easier to discuss, sections including tunnels, shafts, platforms and passenger's entrances are numbered as shown in Figure 2. It is supposed that fire takes place at section 204, a tunnel section between tunnel exhaust shafts and station G1. Two kinds of fire cases are studied. Fire case 1 is that fire starts at the front part of a train moving to station G1, as shown in Figure 3. In this case, the air flow direction should be to station G1 so that the passengers on the train can escape safely from the burning train to the station F1. Fire case 2 is that fire starts at the front part of a train leaving station G1 as shown in Figure 4. In this case, the airflow direction should be from G1 to F1 to help the passengers on burning train to escape to station G1.

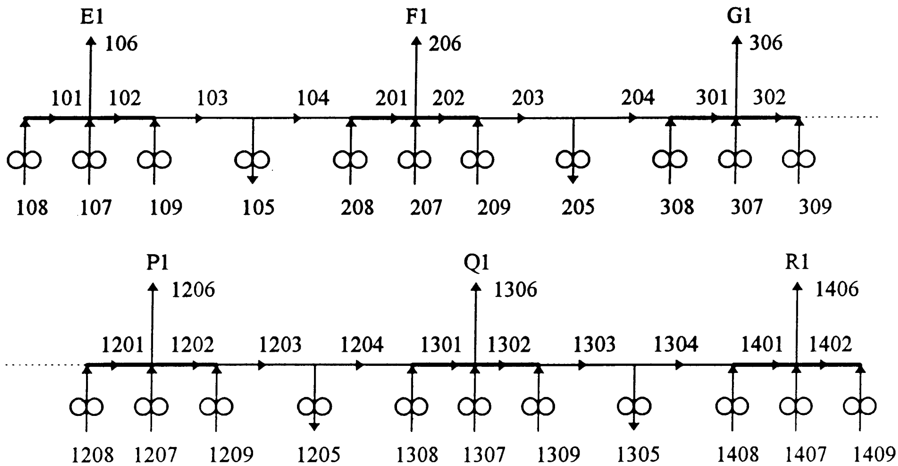

Figure 2 Section number in fire case

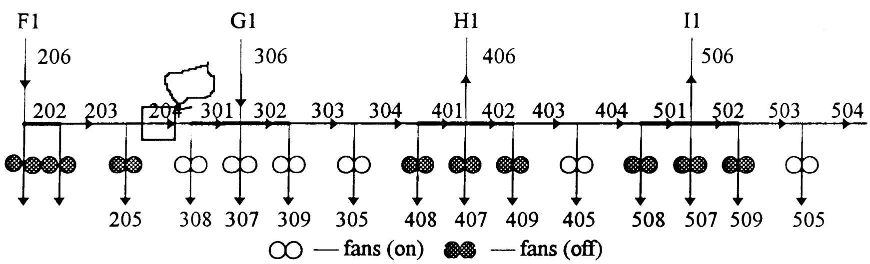

Figure 3 Number and direction of sections in fire case 1

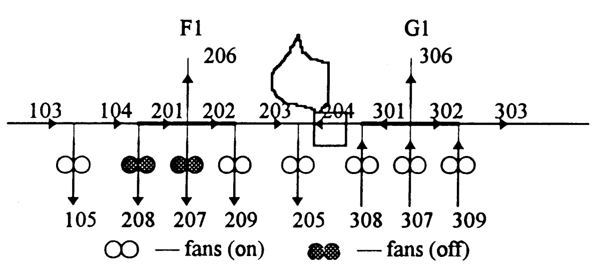

Figure 4 Number and direction of sections in fire case 2

Figure 5 shows the temperature of different branches in fire case 1.

Figure 6 shows the smoke concentration of different branches in fire case 1.

Figure 7 shows the velocity of branch 204 and 306 in fire case 1. It can be seen the air speed of 306 is higher than 2 m/s during the first 30 minutes. So it is safe for patrons

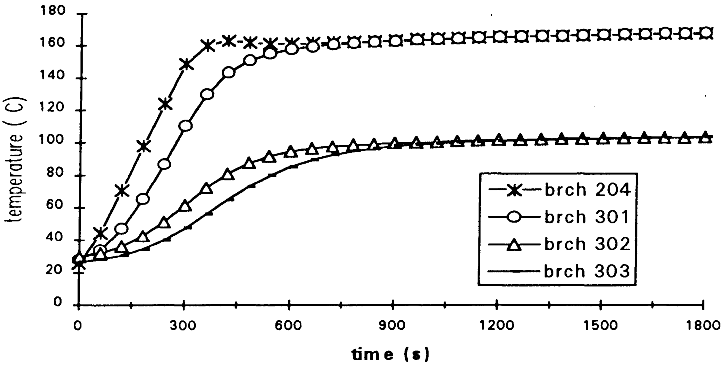

Figure 5 Temperature of different branches in fire case 1

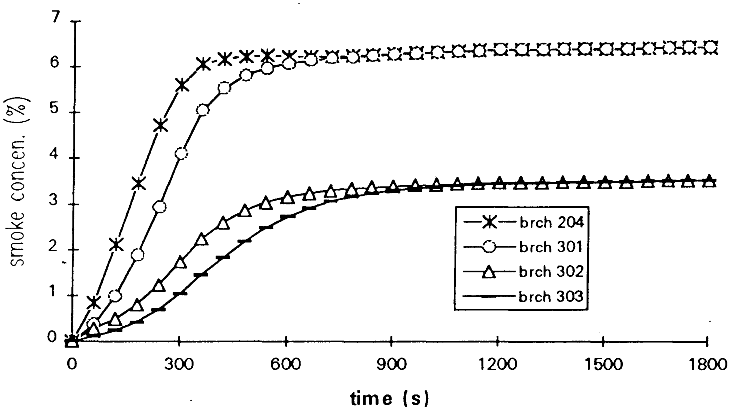

Figure 6 Smoke concentration of different branches in fire case 1

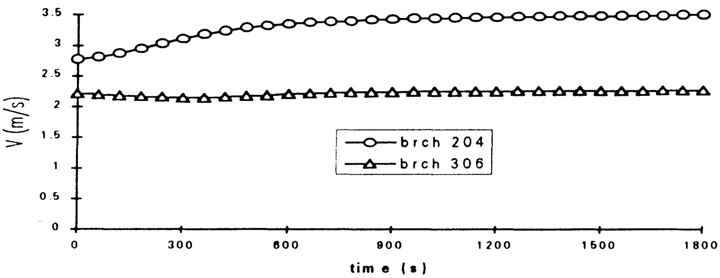

Figure 7 Air velocity of branch 204 and 306 in fire case 1

escaping from platform to ticket hall. Air speed of 204 is 2.77m/s at the beginning, it rise to 3.18m/s after 6 minutes, then to 3.5m/s after 30 minutes due to the chimney effect. If fan 505 does not work, in the first 12 minutes, air speed in 306 varies in the range of 1.9m/s to 2.0m/s as shown in Figure 8. This value is below the code requirement.

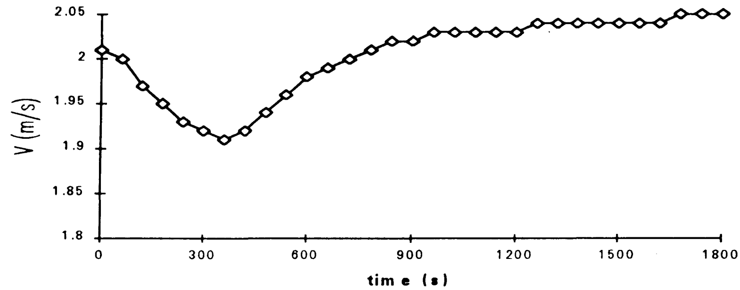

Figure 8 Air velocity of branch 306 in fire case 1 when fan 505 does not function

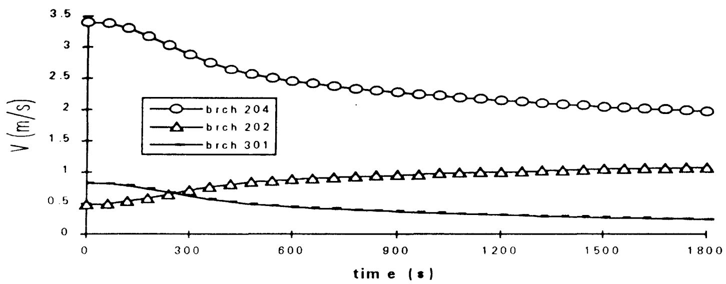

Figure 9 Air velocity of different branches in fire case 2

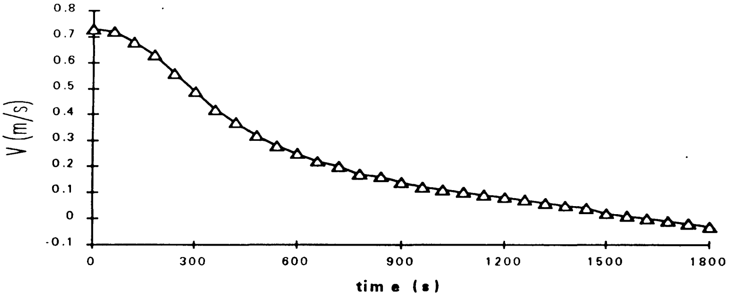

Figure 10 Air velocity of branch 301 in fire case 2

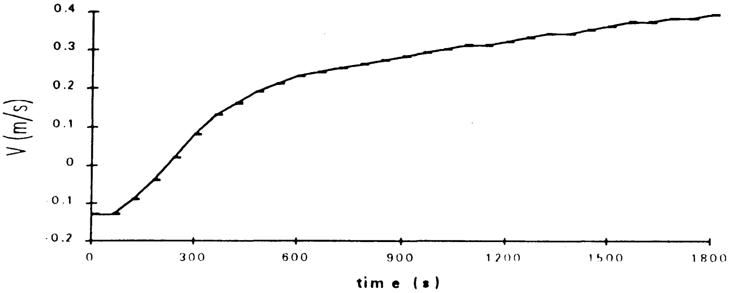

Figure 11 Air velocity of branch 202 in fire case 2 when fan 105 works instead of 209

Figure 9 shows the air speed of branch 204, 202 and 301 in the first 30 minutes in fire case 2. It can be seen that in the first 30 minutes air speeds of branch 204 and 301 decrease gradually and speed of branch 202 increases gradually. This phenomenon is due to the chimney effect.

If fan 209 does not work, air flow direction from platform 301 to 204 will change reverse after 28 minutes, and then smoke will get into station G1 (See Figure 10). Although the passengers of station G1 may have all leave the subway system, it may bring up more cleaning work for the personnel to do.

If exhaust fan 105 works instead of 209, smoke will move to station F1 in the first 3 minutes as shown in Figure 11. After 3 minutes, the flow-rate changes direction due to the chimney effect.

Therefore, if fire takes place at bottom of Line #1, the most reasonable ventilation schemes for fire emergency are:

a) for fire case 1: fans 305, 405 and 505 work normally as exhaust fans; fans 307, 308 and 309 work reverse as exhaust fans.

b) for fire case 2: fans 205 and 209 work as exhaust fans; fans 307, 308 and 309 work as blowers.

If fire takes place at the middle part or the top part of Line #1, the situation will be quite different because there is not so strong chimney effect. However, it is easier to deal with such case and will not be mentioned here.

4 CONCLUSIONS

A theoretical model about smoke movement in tunnel network is presented. The model includes a field model in the fire origin section and network model in other sections of the tunnel network.

By using the model, ventilation schemes during fire emergency in Tehran Subway Line #1 are studied. Two schemes are recommended for two different fire cases.

If fire takes place at bottom of subway line like Tehran Line #1, the most reasonable ventilation schemes for fire emergency are:

a) for fire case 1: fans 305, 405 and 505 work normally as exhaust fans; fans 307, 308 and 309 work reverse as exhaust fans.

b) for fire case 2: fans 205 and 209 work as exhaust fans; fans 307, 308 and 309 work as blowers.

It is found that chimney effect is a very important factor to influence smoke movement in tunnel network, especially when the track slope is very high.

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