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Unsteady 2-Dimension Computational Modeling of Accidental Firing in Tunnels

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Abstract

All tunnels require ventilation to maintain acceptable levels of contaminants produced by vehicle engines during normal traffic operation (normal ventilation), and to remove and control smoke and hot gases during a fire emergency (emergency ventilation) ref. (7).

To protect passengers, personal and equipment in a tunnel fire, it is important to understand and predict the temperature distribution through the tunnel during the tunnel fire. In this paper, a computer program (Tunnel) has been built to investigate the temperature profile along the tunnel for passenger car and three passenger cars with and without ventilation by using (explicit F.D) method .

In this paper, also we will study the effect of the system ventilation on the temperature profile and estimate the required time to return temperature to ambient value for passenger car and three passenger cars.

الخلاصـــــــة

جميع ألأنفاق تتطلب تهوية للحفاظ على مستويات مقبولة من المواد الملوثة التي تنتج من محركات الشاحنات خلال عمليات المرور الطبيعية (تهوية طبيعية)، وللتخلص من الدخان والغازات الحارة والسيطرة عليها خلال الحريق الطارئ (تهوية طارئة).

*لتأمين الركاب، ألأشخاص والمعدات في حريق ألأنفاق، من المهم أن نفهم وأن نتبنى توزيع درجات الحرارة على طول النفق خلال حريق ألأنفاق. في هذا البحث لقد تم بناء برنامج **(Tunnel)** لبحث توزيع درجات الحرارة على طول النفق في حالة حريق سيارة ركاب واحدة أو ثلاث سيارات داخل النفق مع أو بدون نظام التهوية باستخدام أسلوب **(Explicit F.D)**.*

وفي هذا البحث أيضا سوف ندرس تأثير نظام التهوية على توزيع درجات الحرارة والوقت المطلوب لإرجاع درجات الحرارة إلى درجة حرارة المحيط في حالة حريق سيارة ركاب واحدة أو ثلاث سيارات داخل النفق.

1. Introduction

A road tunnel is an enclosed facility that carries motor vehicles. A road tunnel can run under water, through mountains, or be an urban type. Tunnels may also be created by the development of air-right structures over a roadway and overbuilds of the road way [1].

The continuous increase in traffic requires a continuous improvement of the roads and, correspondingly, of the tunnels, to avoid even greater environmental impact [2].Tunnel fires, can occur over accidental spills of flammable fluids from tank Lorries or tank cars. Other fire sources can be burning vehicles or freight [3].

Fires in road and rail tunnels are an international problem. Safety is one of the major concerns in the design of tunnels and tunnel systems. In the tunnel environment, fire and smoke represent a serious hazard to which people may be exposed [1].

Unfortunately, experimental vehicle fires have shown that very large rates of heat release are possible for example; single heavy loads vehicle carrying furniture can reach a rate of heat release in excess of 100MW.Such a fire will produce flames with a length much greater than the height of most tunnels and it is clearly important to determine the variation of critical velocity for such fire [4].

Critical velocity is defined as the minimum velocity of the ventilation system necessary to avoid the back layering, i.e. the smoke moving in the opposite direction of the ventilation system [2].

Ventilation may be provided by natural means, by the traffic-induced piston, or by mechanical equipment. The choices of what ventilation system to use depend on several parameters that include: tunnel length, cross-section and grade, surrounding environment, traffic volume, and construction cost [1].

The aim of this work is to obtain a mathematical model to predict the critical velocity for a scaled tunnel. Numerical method is used to investigate the influence of the parameters that affect the fire in tunnel.

2. Theoretical Modeling

2-1 Physical Model

The test tube shown in **Fig.(1)**, is made of fireproof concrete, with Pyrex glass which represents the testing chamber. Its total length is 6 meters, of semi-circumferences cross section, with the internal radius of 0.15 meters, the height from the floor is 0.2 m and the width of the floor level is 0.28m, as shown in **Fig.(2)**. This is in fact has been adopted by ref.(2) to provide experimental results. The same dimensions have been considered in the present work to carry out the numerical analysis.

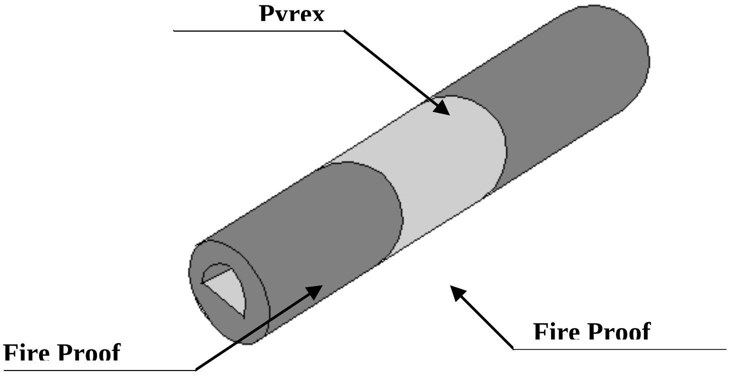

Figure (1) Model tunnel used in theoretical work [2]

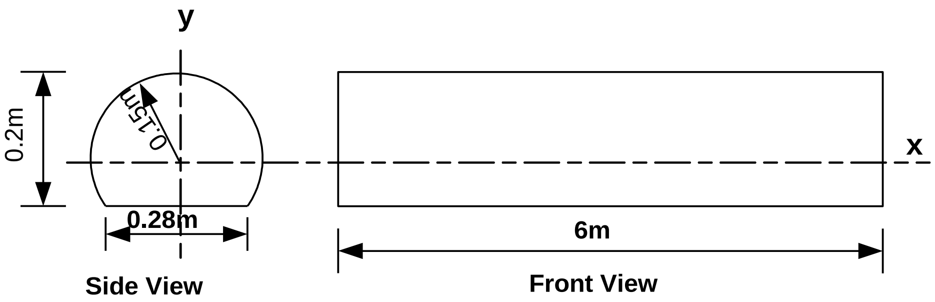

Figure (2) Dimensions of tunnel [2]

2-2 Thermal Power

The world Road Association (Permanent International Association of Road Congresses) PIARC [5] provides some empirical recommendations of the fire characteristics for different types of fire scenarios in road tunnels **Table (1)**.

In terms of smoke volume flow rate, the comparison with PIARC data, presented in [5], reveals good agreement when the characteristic height of the computation is taken as the standard tunnel height of 5m.

The model and full-scale heat release rated Q_{mod} and $Q_{full\ scale}$ are related by Eq.(1) [4].

$$\frac{Q_{mod}}{Q_{fullscale}} = \left(\frac{H_{mod}}{H_{fullscale}}\right)^{5/2} \quad \text{..............................} \quad (1)$$

where:

H_{mod} and $H_{full\ scale}$ are the heights of model and full-scale tunnels respectively.

Table (1) PIARC Recommendations for different types of fire scenarios [5]

Fire Type	Passenger Car	Passenger Three Cars
Total Heat Release Rate(MW)	4	8

2-3 System of Ventilation

According to ref. (1), there are four longitudinal ventilation types for car tunnels. The jet fans type has been assumed in this analysis, by a fan on the vault, scaled from a real fan and with adjustable velocity [1], as shown in **Fig.(3)**.

The critical velocity is given by the equation below [4].

$$U_{cr}=\left[\frac{gQH}{\rho\ T_o C_p A}\right]^{1/3} \qquad \text{(2)}$$

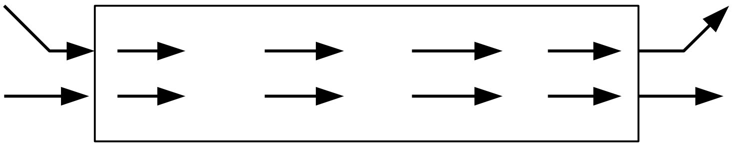

Figure (3) Longitudinal ventilation system

2-4 Governing Equation

The case under study is unsteady-state two-dimensional, with thermal conductivity, and pressure assumed constant and velocity at x-direction only as shown in **Fig.(4)**.

It follows that the following heat transfer phenomena are present in the tunnel:

1. Conductive on heat transfer in x-direction and in y-direction.
2. Change in internal energy.

$$\frac{dE}{dt}=\rho C_p d_x d_y \frac{\partial T}{\partial t} \qquad \text{(3)}$$

After taking energy balance to the element, the following will be obtained:

$$q_x+q_y+Qc_x=q_{y+dy}+q_{x+dx}+Qc_{x+dx}+\frac{dE}{dt} \qquad \text{(4)}$$

Assuming no change in velocity in X-direction $\left(\frac{\partial u}{\partial x}=0\right)$, the Eq.(4) becomes:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \frac{\partial T}{\partial X} = K \frac{\partial^2 T}{\partial Y^2} + K \frac{\partial^2 T}{\partial X^2} \quad \text{..} \quad (5)$$

By dividing Eq.(5) by ρC_p ,the following will be obtained:

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial X} = \alpha \frac{\partial^2 T}{\partial X^2} + \alpha \frac{\partial^2 T}{\partial Y^2} \quad \text{..} \quad (6)$$

where:

$\alpha = \frac{K}{\rho C_p}$

u: critical velocity

Initial and boundary conditions are obviously needed which are given by the temperature field, the condition of fire and the ventilation system.

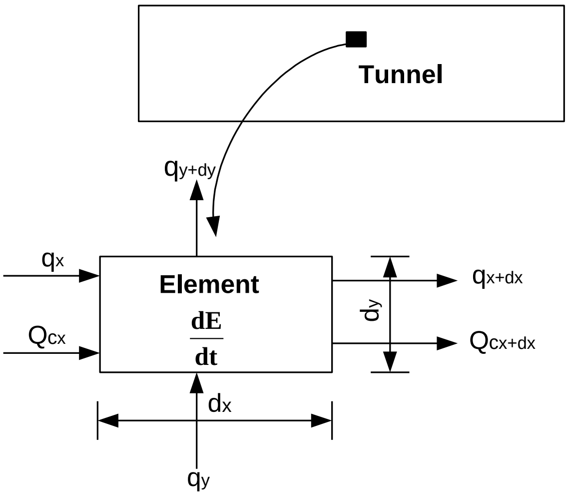

Figure (4) Element from tunnel

2-5 Assumption Initial and Boundary Conditions

Suitable assumptions to simplify the solution and summarized as:

1. The phenomena is unsteady, change in the internal energy take place ($\frac{\partial E}{\partial t} \neq 0$).
2. Constant thermal conductivity $k \neq k(T)$, $C_p \neq C_p(T)$.
3. The velocity in x-direction not change, $\frac{\partial u}{\partial x} = 0$.
4. The velocity adopted in the governing equations is the critical velocity $U=U_{cr.}$
5. Constant pressure field while the initial conditions are:

$T=T_{amb}$ at $t \leq 0$ $\frac{\partial E}{\partial t} = 0$ at $t \leq 0$

and the boundary conditions are:

at x=0

$$-kA\frac{\partial t}{\partial x} = \text{convective heat flux + the thermal power of the fire.}$$

at x=L

at any time $t=t_o$

The Tunnel wall is assumed adiabatic, i.e. at y=0 & y=H, $\frac{\partial T}{\partial y} = 0$

2-5-1 Initial Condition

In the first step, the initial temperature field is the ambient temperature, set equal to 293 k.

2-5-2 Boundary Condition

The general form of the boundary condition at X=0 is [2]:

$$-AK\frac{\partial T}{\partial X}\Big|_{x=0} = \left(\rho C_p AuT_o - \rho C_p AuT\right) + Q_{mod}\frac{y}{H} \qquad x = 0, \forall y \text{ and } \forall t \text{..........} \textbf{(7)}$$

The first term on the right side takes into account the convection heat flux, and the second term is the thermal power of the fire, considered as linearly distributed to simulate the shape of the flame.

For the boundary condition at X=L, the hypothesis of semi-infinite domain is used which leads to:

$$T = T_o \qquad X = L, \forall y \text{ and } \forall t \text{ ....} \textbf{(8)}$$

The tunnel walls assumed to be adiabatic:

$$\frac{\partial T}{\partial Y} = 0 \qquad \text{y=0, y=H, } \forall x \text{ and } \forall t \text{ ....} \textbf{(9)}$$

3. Computational Procedure

The tunnel is divided into segments so that any two adjacent nodes are separated by an increment ΔX at x-direction and ΔY at y-direction as shown in **Fig (5)**.

By using (Q-basic) language, a computer program is developed to solve numerically two-dimensional linear partial differential equations using finite difference method (Explicit Method). The flow chart of the computer program is shown in **Fig.(7)**.

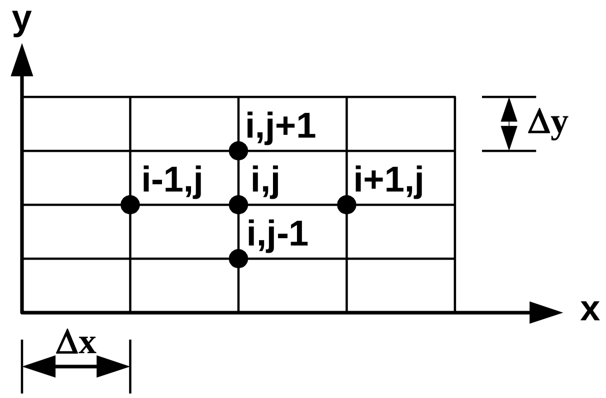

Figure (5) Typical finite difference grid for equation (6)

Equation (6) can be solved by using finite difference explicit method for local error order of (o) h^2 as following [6].

$$\frac{\partial T}{\partial t}=\frac{T_{i,j}^{n+1}-T_{i,j}^{n}}{\Delta t}\quad\text{.......} \quad (10)$$

$$\frac{\partial^2 T}{\partial x^2}=\frac{T_{i+1,j}^{n}-2T_{i,j}^{n}+T_{i-1,j}^{n}}{\Delta x^2}\quad\text{.......} \quad (11)$$

$$\frac{\partial^2 T}{\partial y^2}=\frac{T_{i,j+1}^{n}-2T_{i,j}^{n}+T_{i,j-1}^{n}}{\Delta y^2}\quad\text{.......} \quad (12)$$

$$\frac{\partial T}{\partial x}=\frac{T_{i+1}^{n}-T_{i-1,j}^{n}}{2\Delta x}\quad\text{.......} \quad (13)$$

After arrangement:

$$\begin{aligned}T_{i,j}^{n+1}=&\left[\alpha\left(\frac{T_{i+1,j}^{n}-2T_{i,j}^{n}+T_{i-1,j}^{n}}{\Delta x^2}\right)+\alpha\left(\frac{T_{i,j+1}^{n}-2T_{i,j}^{n}+T_{i,j-1}^{n}}{\Delta y^2}\right)\right]\\&+T_{i,j}^{n}-u\Delta t\left(\frac{T_{i+1,j}^{n}-T_{i-1,j}^{n}}{2\Delta x}\right)\end{aligned}\quad\text{.......} \quad (14)$$

Note: Subscript (n) means at t=Δt & Subscript (n+1) means at t=t+Δt.

At each time step the temperature solution is carried out first at (n), another time (n+ 1) can then be taken, and the process repeated.

In this search we have been divided the tunnel into elements Δx at x-direction and into Δy at y-direction as shown in **Fig.(6)**.

We have been taken $\Delta x=0.6m$, and $\Delta y=0.01m$ and for best solution we have been taken $\Delta t=.00001sec$ in order to convergence the solution.

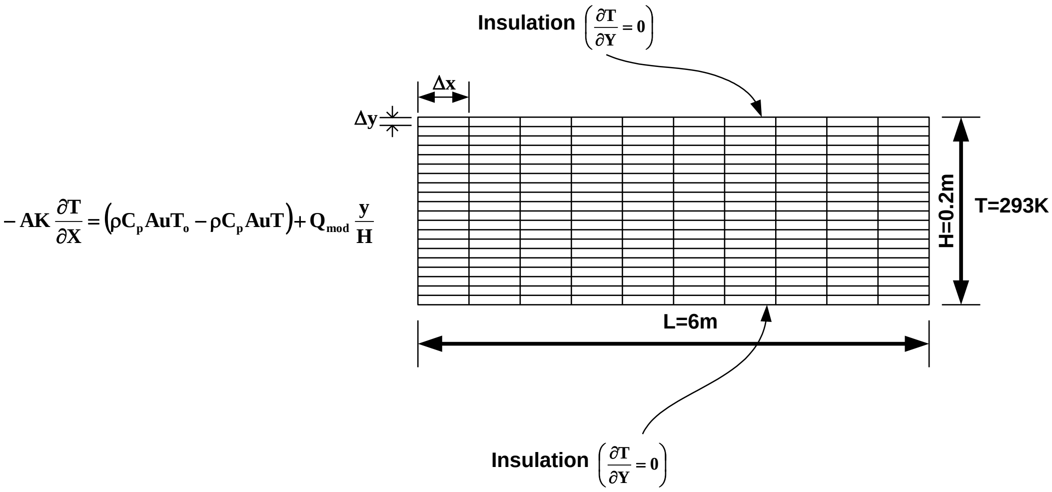

Figure (6) Mesh generation of tunnel

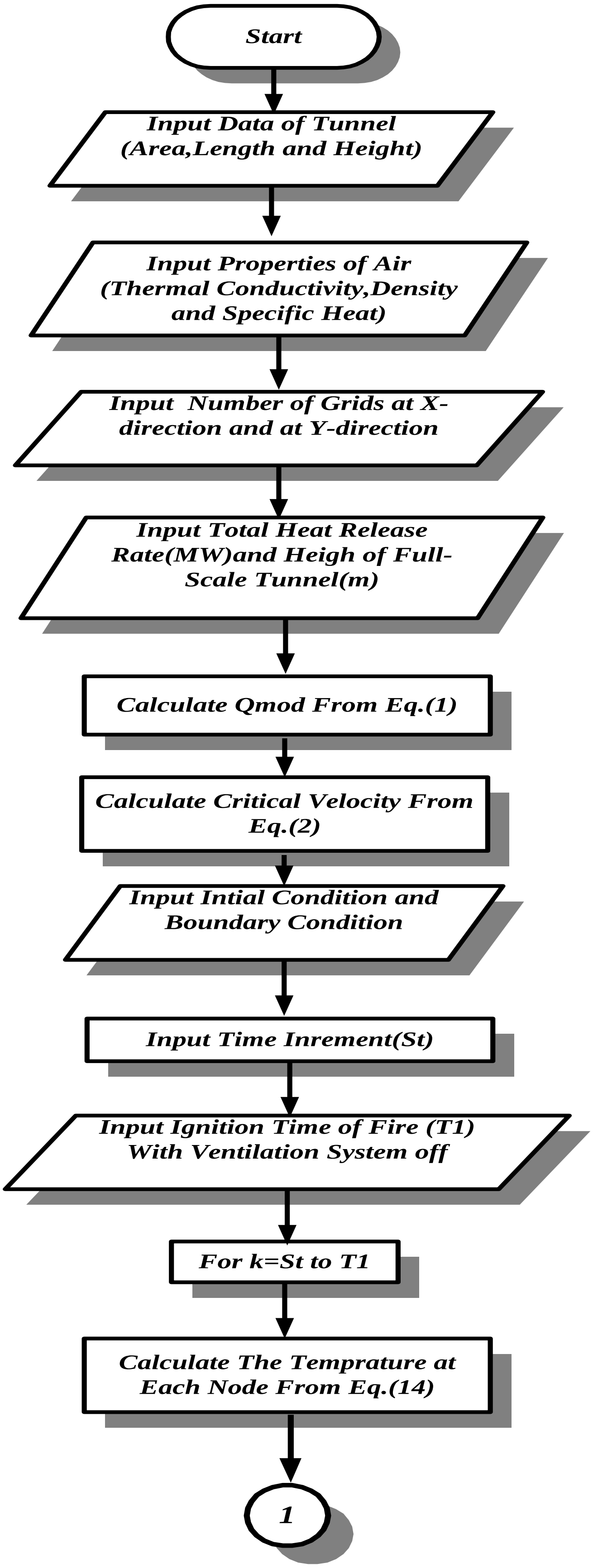

Figure (7) Flowchart of computer program tunnel

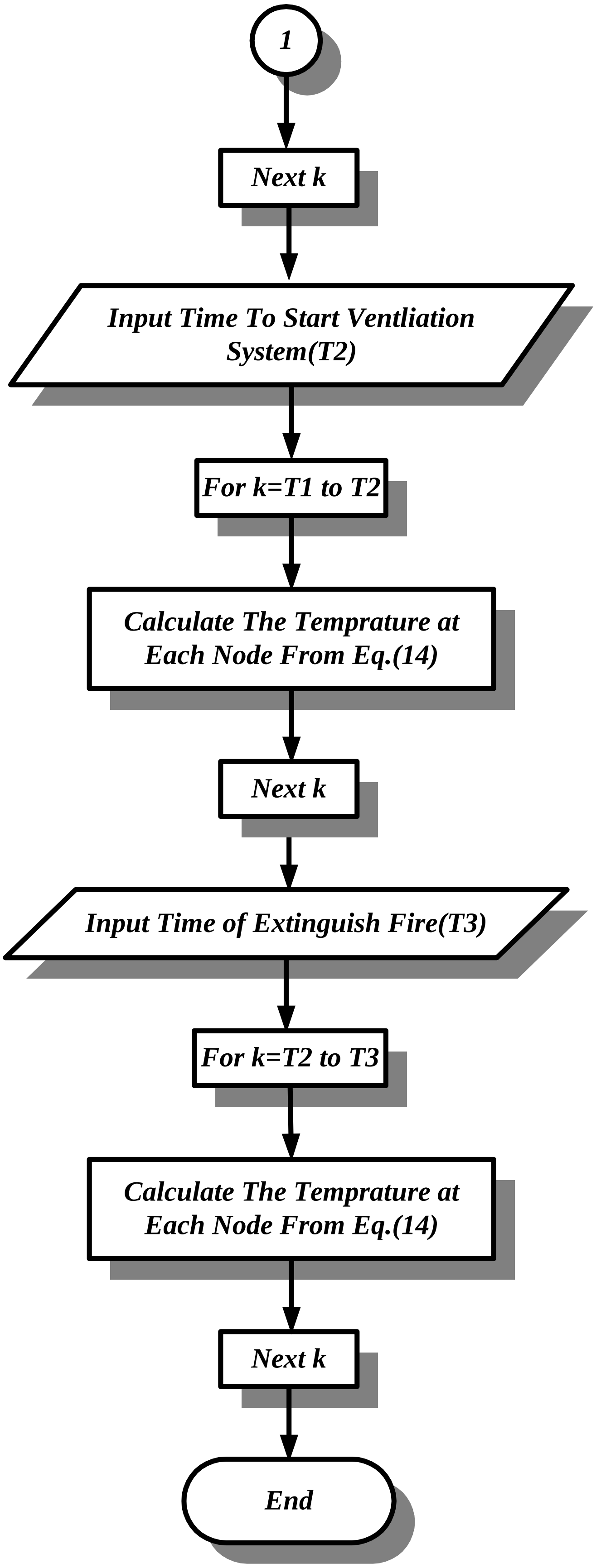

Figure (7) Continued

4. Results and Discussion

The fire tests went through three different sequential steps:

1. Ignition of fire with ventilation system off (u=0).
2. After 230-240 seconds from the start of the fire, ventilation also starts.
3. At the end, fire is extinguished, but ventilation system was remains on (Q=0).

Selected results from run tunnel **Figs.(8)**, **(9)**, **(10)** and **(11)** for passenger car and **Figs.(12)**, **(13)**, **(14)** and **(15)** for three passenger cars when the fire is ignited at time 230 sec, the temperature starts to increase with time.

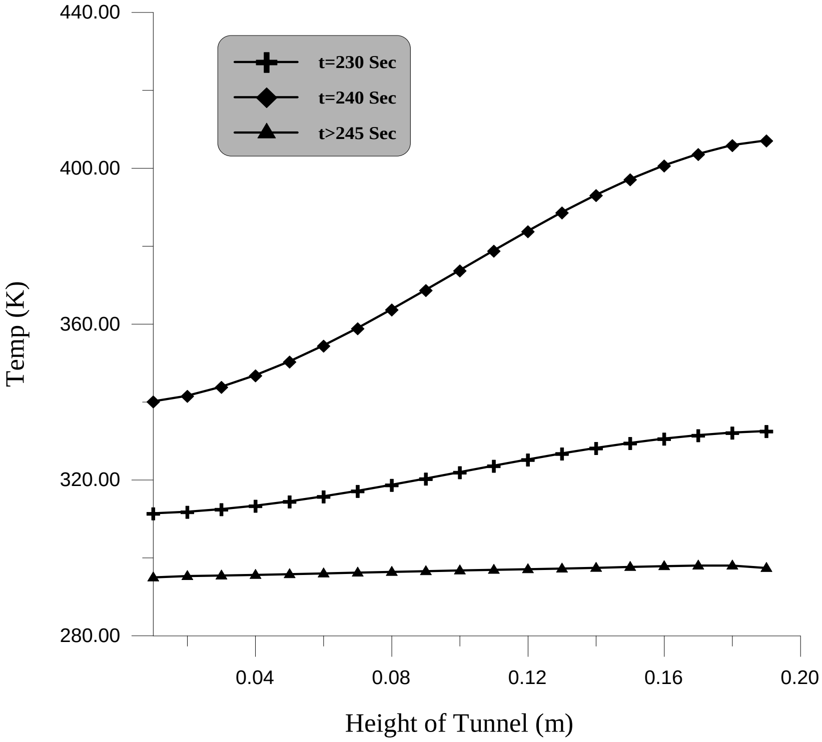

Figure (8) Temperatures distribution at passenger car in the model tunnel and at various heights distance from the fire 0.6m

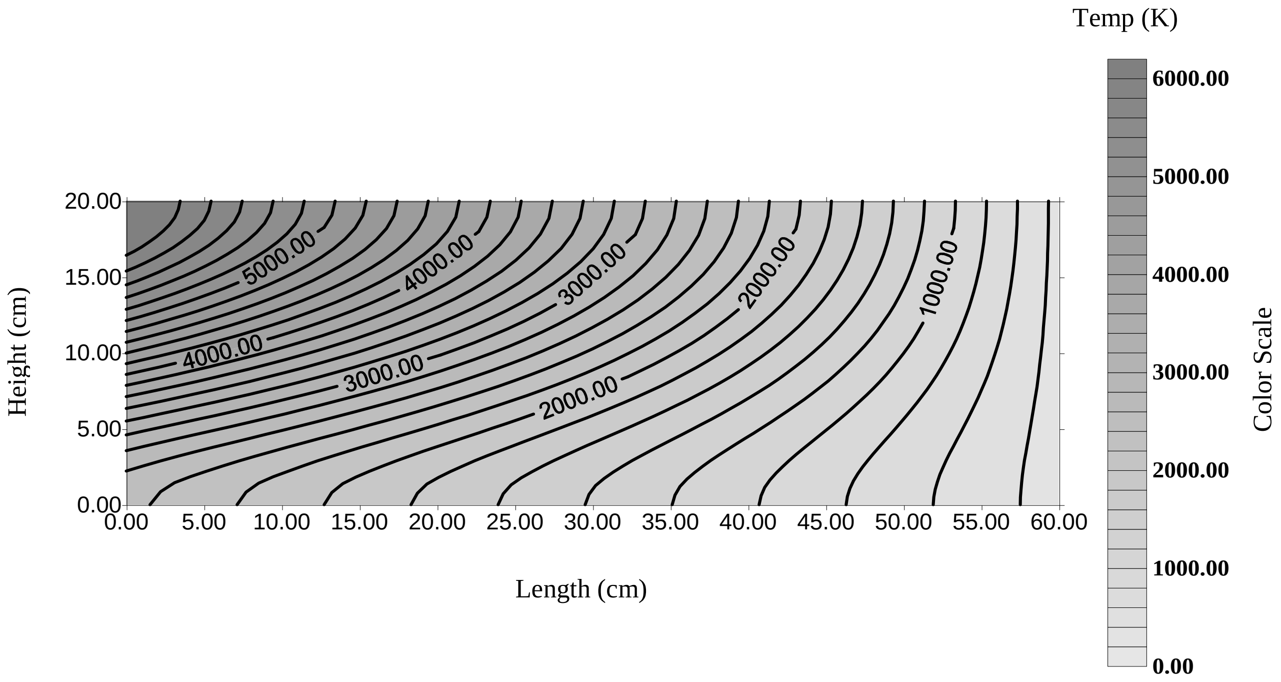

Figure (9) Temperatures distribution at passenger cars in the tunnel model at various heights distance from the fire 0.6 m, and at time 230 sec

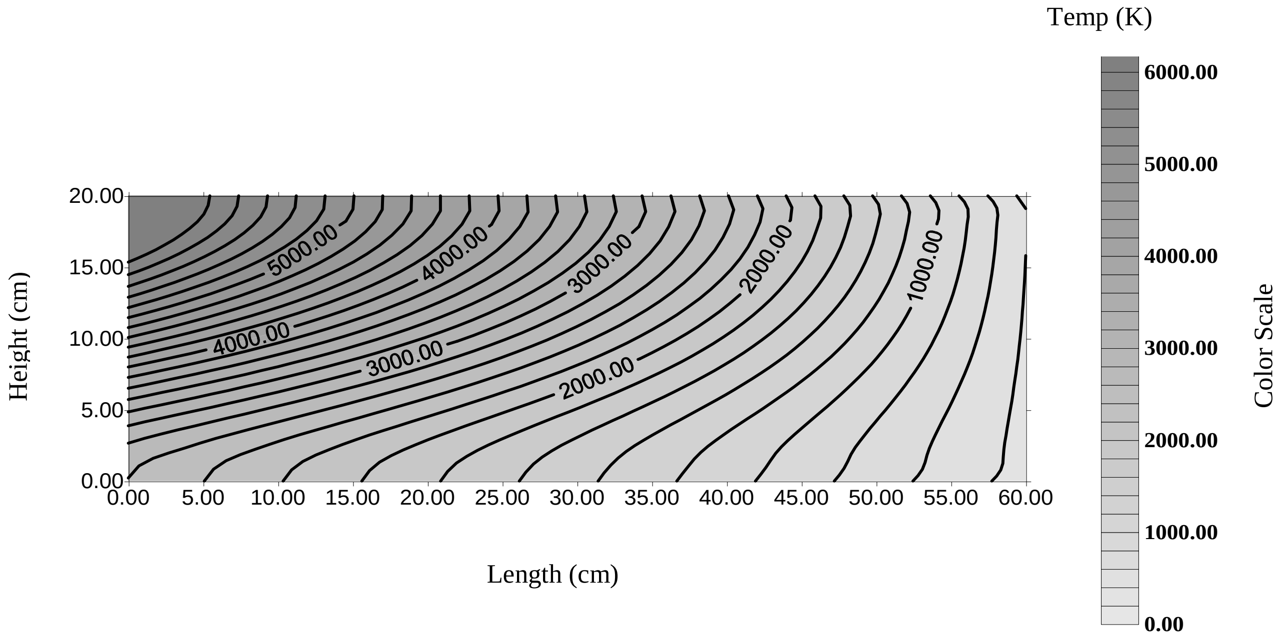

Figure (10) Temperatures distribution at passenger cars in the tunnel model at various heights distance from the fire 0.6 m, and at time 240 sec

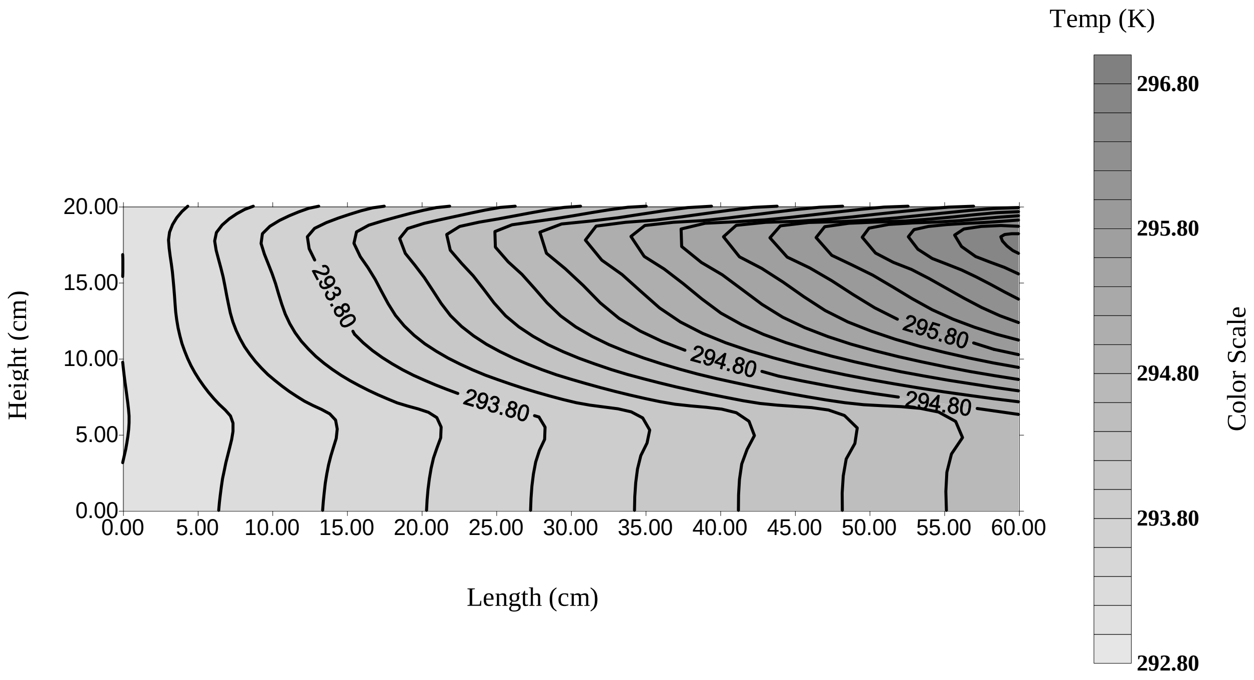

Figure (11) Temperatures distribution at passenger car in the tunnel model at various heights distance from the fire 0.6 m, and at time greater than 246 sec

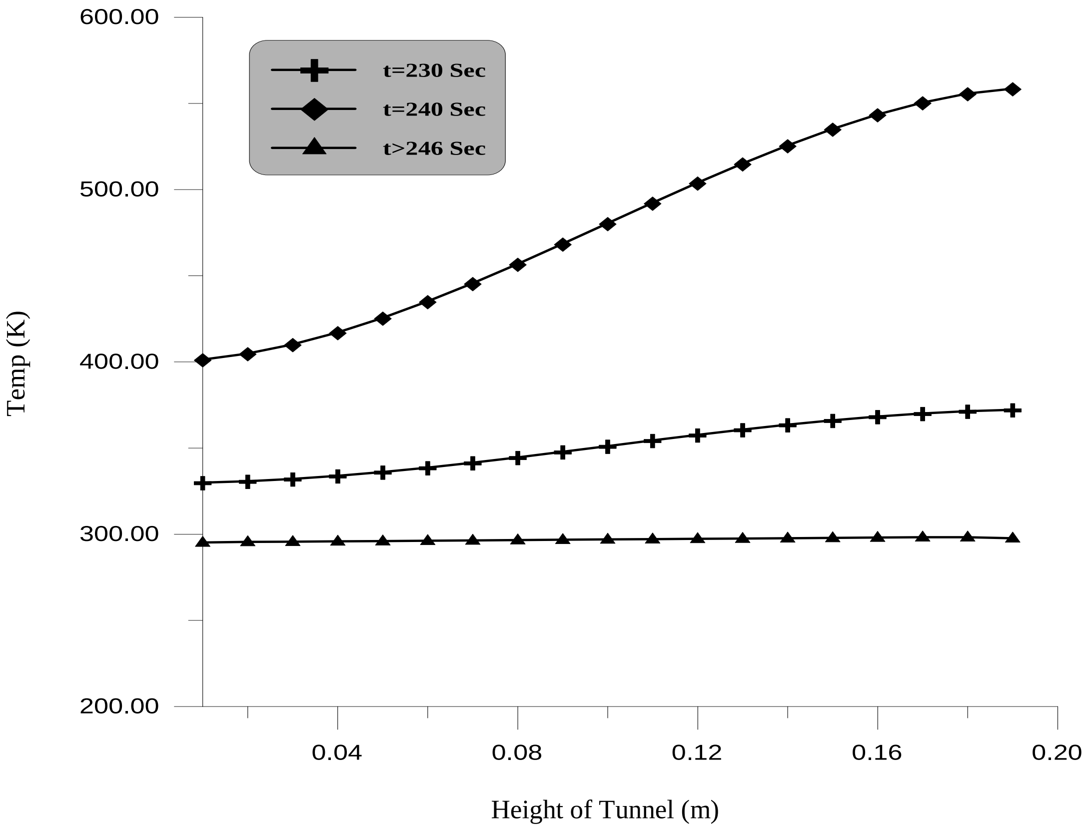

Figure (12) Temperatures distribution at three passenger cars in the model tunnel and at various heights distance from the fire 0.6m

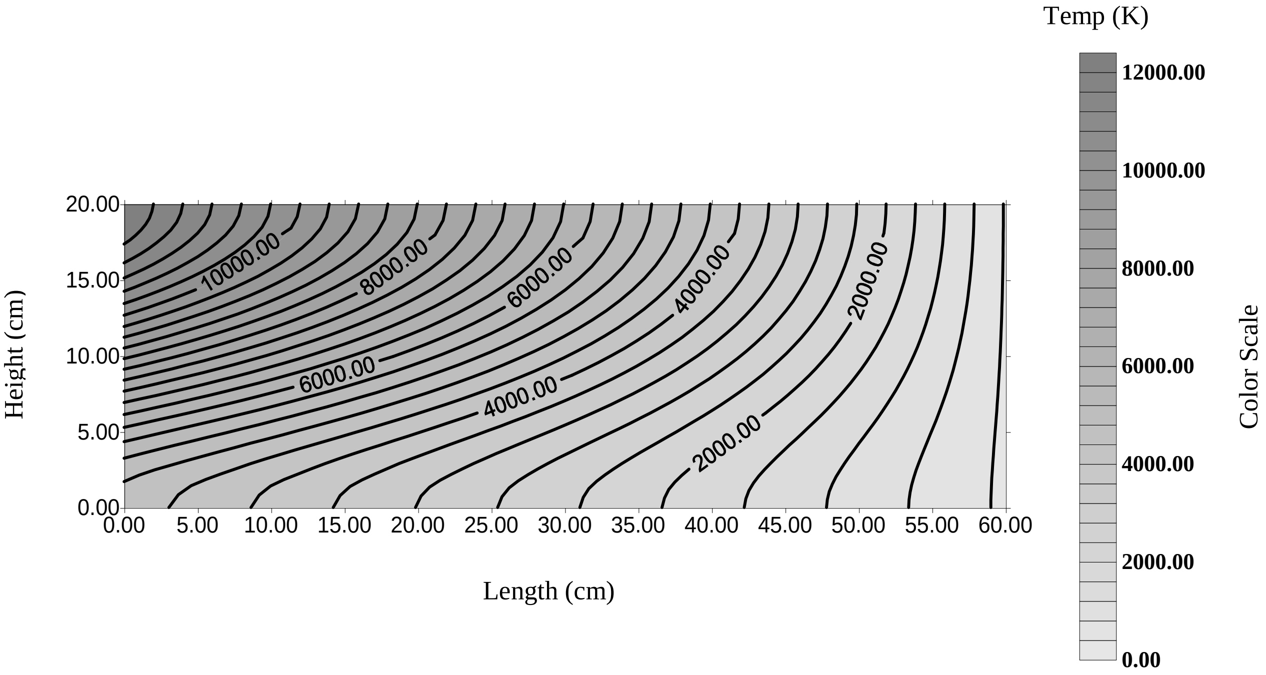

Figure (13) Temperatures distribution at three passenger cars in the tunnel model at various heights distance from the fire 0.6 m, and at time 230 sec

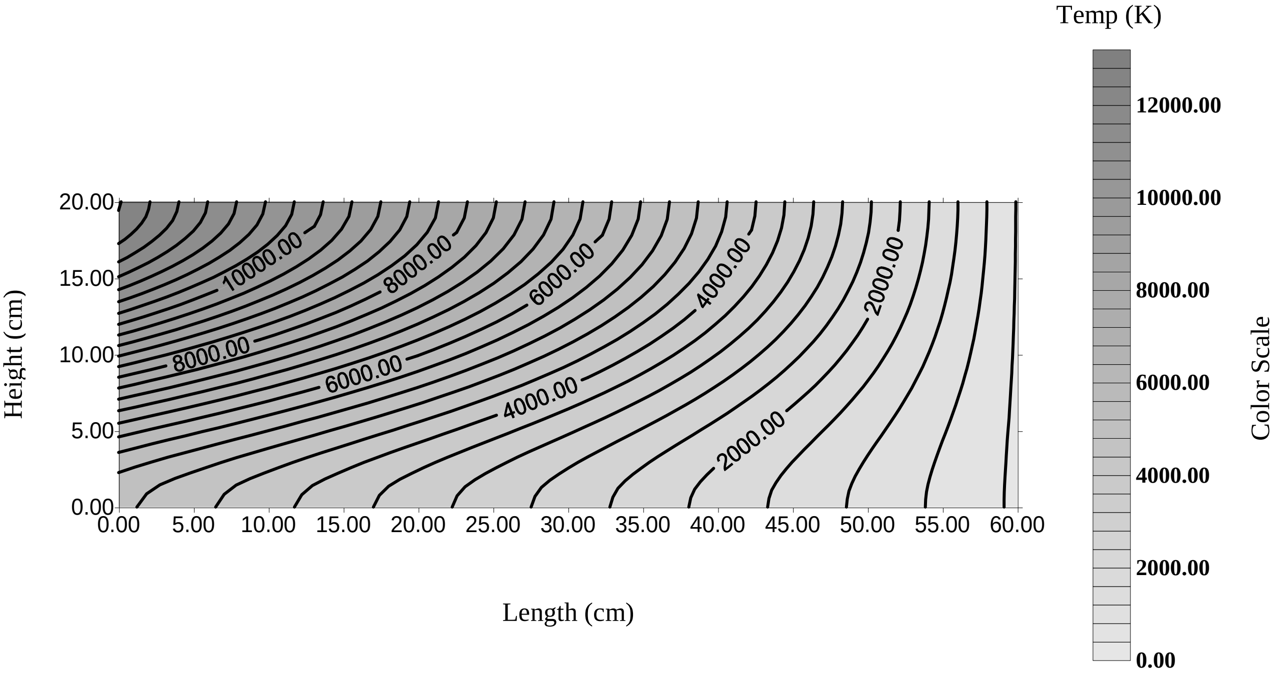

Figure (14) Temperatures distribution at three passenger cars in the tunnel model at various heights distance from the fire 0.6 m, and at time 240 sec

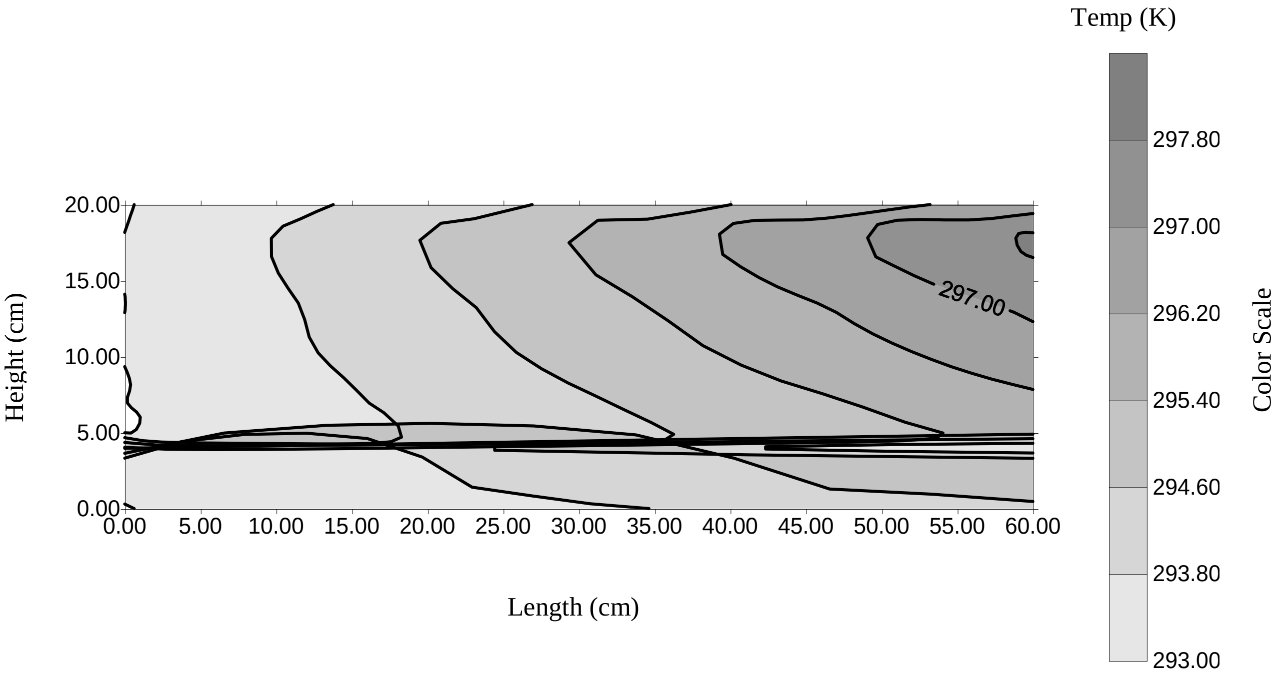

Figure (15) Temperatures distribution at three passenger cars in the tunnel model at various heights distance from the fire 0.6 m, and at time greater than 245 sec

Then, the ventilation system is put on during the period (239-240) sec; we can observe that the temperature continues to increase .After the end of fire and at time greater than 240 sec, but with system ventilation on, the temperature eventually returns to ambient value.

We can observe that the highest temperature is reached near the ceiling and the temperature returns to the ambient value at time greater than 245 sec and 246 sec for passenger car and three passenger cars respectively as shown in **Figs.(11)** and **(15)**.

The ventilation system necessary to avoid the back layering and to return temperature to ambient value in passenger car is less than in three passenger cars ,it means the time required to return temperature to ambient value in three passenger cars is greater than in passenger car because the thermal power in passenger car is less than the thermal power in three passenger cars and from this we can be concluded, when the thermal power is greater ,we will need system ventilation is greater as shown in Eq.(2).

In the program we have been noticed that the time increment must be smaller when the velocity is bigger, it means when the velocity is bigger (turbulent flow) the time increment must be smaller in order to convergence the solution.

5. Conclusion

In the present analysis, a computer program has been developed to calculate the temperature distribution created in any tunnel due to a normal heat sources e.g. explosion .Also, the case study adopted is a car tunnel exposed to burn out of passenger car & then the model has taken into account a three passenger cars any heat release, any critical velocity and at any time are capable to be predicated.

6. References

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Notations

The following symbols are used in this paper:

A: Section of Tunnel in m^2
C_p: Specific Heat in J/kg.K
H: Height of Tunnel in m
$H_{fullscale}$: Full Scale Height of Tunnel in m
H_{mod}: Model of Height Tunnel in m
K: Thermal Conductivity in W/m.K
Q: Thermal Power in W
$Q_{fullscale}$: Full Scale Thermal Power in W
T: Temperature in K
T_o: Initial Temperature in K
U: Velocity in m/sec.
U_{cr}: Critical Velocity in m/sec.
X: Horizontal Coordinate in m
Y: Vertical Coordinate in m
α: Thermal Diffusivity in m^2 /sec
ρ: Density in kg/m^3