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Research on Design Fire Curves in Tunnels

Mostafa Monfared Mosghani *,1
* Shiraz University of Technology

(§Correspondent author's E-mail: monfared1363@gmail.com)

ABSTRACT The rate at which energy is released, generally known as the heat release rate is the most important variable, which characterizes the behaviour of the fire. Design fire curves are essential inputs required by a fire safety engineered approach to the fire safety design of tunnels and any appraisal fire protection measures in existing tunnels. In this research, at first, the fire phases are described and then the different mathematical representations for design fire curves are investigated and compare with each other. The author believes that the information presented in this research will be useful for who are interested in field of fire or non-premixed combustion modelling.

Keywords design fire curve, heat release rate, tunnel, non-premixed combustion.

INTRODUCTION

In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams. This is in contrast to premixed systems. One of the most important examples of non-premixed combustion is fire. Recently, several big fire disasters have occurred in the tunnels, so the investigation of the fire in tunnels is so important. Design fire in tunnels are usually given as the peak heat release rate that is fire power in MW, although it become more and more common for engineers to combine the with the peak heat release rate with the fire growth rate because the fire growth rate will be crucial in determining whether those caught in the fire can escape. Moreover, researchers showed that the fire growth rate is more important than the peak heat release rate when investigating the safety of people trapped in fire smoke [1]. A fire may include some or all of the following phases of development, which are also illustrated in Figure 1[2].

a) Incipient phase: characterized by a verity of fire sources, such as smouldering or flaming fire.
b) Growth phase: ignition is the beginning of fire development. At the initial growth phase, the fire will be normally small and localized in compartment. An accumulation of smoke and combustion products in layer beneath the ceiling will gradually form a hotter upper layer in the compartment, with a relatively cooler and cleaner layer at the bottom. With sufficient supplies of fuel and oxygen and without interruption of fire fighting, the fire will grow larger and release more hot gases and combustion products to the smoke layer. The smoke layer will descend as it becomes thicker.

[1]Students of master of science, Mechanical and Aerospace Department, Shiraz University of Technology

c) Flashover phase: in case of fire, developing into flashover, the radiation from the burning flame and the hot smoke layer may lead to an instant ignition of unburned combustible material in the compartment. The whole compartment will be engulfed in fire and smoke.

d) Fully developed phase or post-flashover: after flashover, the fire enters a fully developed stage with the rate of heat release reaching the maximum and the burning rate remaining substantially steady. The fire may be ventilation or fuel controlled. Normally, this is the most critical stage that structural damage and fire spread may occur.

e) Decay phase: after a period of sustained burning, the rate of burning decrease as the combustible material is consumed and the fire now enter the decay phase.

f) Extinction: the fire will eventually cease when all combustible materials have been consumed and there is no more energy being released.

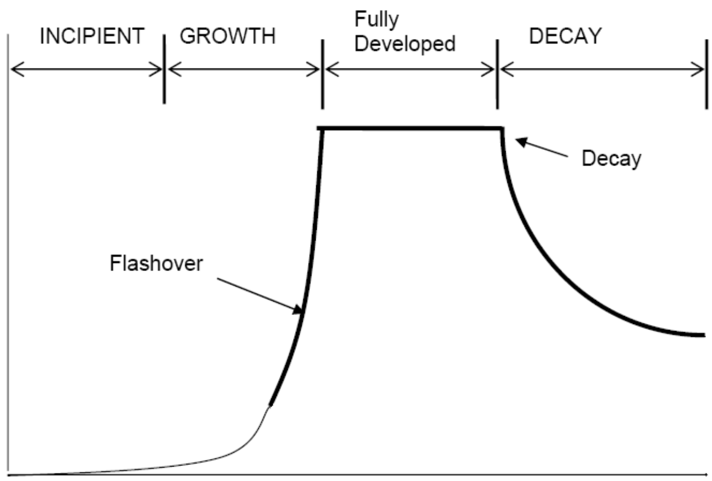

Figure 1: schematic of design fire scenario
(Axes: horizontal: time; vertical=temperature or heat release rate)

Design fire curves:

There are numerous methods available to mathematically represent a design fire curve in tunnels. These include different types of fire growth rates, e.g. linear growth (αt), quadratic growth (αt^2) or exponential growth ($\alpha(1-e^{-t})$) rate. These growth functions can be combined with a peak heat release rate (HRR) value ($\dot{Q}_{\max}$) and a decay functions ($-t \; or \; e^{-t}$). In building fire safety design, usually the growth rate alone is considered whereas in tunnels the entire fire curve is considered. In the following a summary of four different methods to describe a complete design curve for tunnels is given:

a) Linear growth:

In this method heat release rate, describe as a linear growth from zero to time $t_{\max}$, a constant maximum value to the time t_D and finally a linear decrease from the maximum value to zero to the time t_d [3].

Table 1

Equations for Linear growth method to describe a complete design fire curve for tunnel

HRR as a function of time t (s)	Time interval (s)	Time to maximum HRR (s)	Time to decay start (s)
$HRR = \alpha_{g,L} t$	$0 \le t_{\max}$	$t_{\max} = \frac{\dot{Q}_{\max}}{\alpha_{g,L}}$	$t_D = t_d - \sqrt{\frac{2}{\alpha_{D,L}}\left(\frac{\alpha_{g,L}}{2} t_{\max}^2 + \dot{Q}_{\max}(t_d - t_{\max}) - E_{\max}\right)}$
$HRR = \alpha_{g,L} t_{\max} = \dot{Q}_{\max}$	$t_{\max} \prec t \prec t_D$		
$HRR = \dot{Q}_{\max} - \alpha_{D,L}(t - t_D)$	$t_D \prec t \prec t_d$		

Table 2 shows the design parameters for the linear method for different kinds of vehicles that obtained from experimental results:

Table 2

The design parameters for linear growth method [3, 4]

Type of vehicle	$\dot{Q}_{\max}$ (MW)	$t_{\max}$ (min)	t_D (min)	t_d (min)	$\alpha_{g,L}$ $(MW/\min)$	$\alpha_{D,L}$ $(MW/\min)$
2-3 cars	8	5	25	45	1.6	0.4
1 van	15	5	35	55	3	0.75
1 HGV-no hazardous goods	30	10	70	100	3	1
1 tanker-hazardous goods	200	10	70	100	20	6.7

b) Quadratic growth:

In this approach HRR describe with a quadratic growth from zero to time $t_{\max}$, a constant maximum value to the time t_D and finally an exponential decrease from the maximum value to zero to infinity [5].

Table 3

Equations for quadratic growth method to describe a complete design fire curve for tunnel

HRR as a function of time t (s)	Time interval (s)	Time to maximum HRR (s)	Time to decay start (s)
$HRR = \alpha_{g,q} t^2$	$0 \le t_{\max}$	$t_{\max} = \frac{\dot{Q}_{\max}}{\alpha_{g,q}}$	$t_D = \frac{\chi E_{tot}}{\dot{Q}_{\max}} + \frac{2}{3} t_{\max} - \frac{1}{\alpha_{D,q}}$
$HRR = \alpha_{g,q} t_{\max}^2 = \dot{Q}_{\max}$	$t_{\max} \prec t \prec t_D$		
$HRR = \dot{Q}_{\max} e^{-\alpha_{D,q}(t - t_D)}$	$t \ge t_D$		

In Table 4 proposed design parameters for quadratic methods for different kinds of vehicle:

Table 4
The design parameters for quadratic growth method [5]

Type of vehicle	$\dot{Q}_{\max}$ (MW)	$\alpha_{g,q}$ $(MW/\min^2)$	$\alpha_{D,q}$ $(\min^{-1})$
car	4	0.036	0.06
bus	30	0.36	0.042
Truck	15-30	-	-
Train with Steel contribution	15	0.036	0.06
Subway car with aluminium contribution	35	1.08	0.06

c) Exponential growth-fuel control:
In this method, HRR proposed as a single exponential function of time instead of as a three function of time. This approach use only for fuel control fires. The design parameters are the peak HRR ($\dot{Q}_{\max}$), the total calorific value (E_{tot}), and the parameter n, which is arbitrary chosen parameter with no physical meaning. Based on these parameters, $t_{\max}$ and t_d can be calculated. Other parameters are r and k, which are calculated based on information given [6,7].

Table 5
Equations for exponential growth-fuel control method to describe a complete design fire curve for tunnel

HRR as a function of time t (s)	Time interval (s)	Time to fire duration (s)	Time to decay start (s)
$HRR = \dot{Q}_{\max} \cdot n \cdot r \cdot \left(1-e^{-k\cdot t}\right)^{n-1} \cdot e^{-k\cdot t}$	$t \geq 0$	$t_{\max} = \dfrac{\ln(n)}{k}$	$t_d = \dfrac{1}{k} \cdot \ln\left(\dfrac{1}{1-\beta_d^{\frac{1}{n}}}\right)$

In addition, the parameters r and k are derived from:

$$\begin{cases} r = \left(1 - \frac{1}{n}\right)^{n-1} \\ k = \frac{\dot{Q}_{\max}}{E_{tot}} \cdot r \end{cases} \quad (1)$$

d) Exponential growth-ventilation control:

In this method proposed a fire curve with a steady state period by summing up two exponential curves. This would apply in case of strongly ventilation-controlled tunnel fires [7].

Table 6
Equations for exponential growth-ventilation control method to describe a complete design fire curve for tunnel

HRR as a function of time t (s)	Time interval (s)	Time to fire duration (s)	Time to decay start (s)
$HRR = \dot{Q}_{\max}\begin{pmatrix} 18.96 \cdot e^{-10t/t_d}\left(1 - e^{-10t/t_d}\right)^7 \\ +37.59 \cdot e^{-7t/t_d}\left(e^{-7 \cdot t/t_d} - 1\right)^{20} \end{pmatrix}$	$t \ge 0$	$t_{\max} = 0.24 \cdot t_d$	$t_d = 2.03 \times \frac{E_{tot}}{\dot{Q}_{\max}}$

In above tables, index $\max$ refers to the peak value, D refers to the decay period, d refers the total fire duration, g refers to the growth period, L refers to a linear period, q refers to a quadratic period and tot refers to the total. χ Is the combustion efficiency and β_d is the ratio between the integrated energy at time t_d, (E_{tot,t_d}), and the total energy released in the fire (E_{tot}) and can be arbitrary chosen ($0.97-0.99$). The linear fire growth rate ($\alpha_{g,L}$) and linear decay rate ($\alpha_{D,L}$) have been calculated based on the given data.

In order to demonstrate the use of the equations mentioned, an example has been chosen from table 2. It is a heavy good vehicle (HGV) with no hazardous goods, with a total calorific value of 125 GJ, peak HRR equal to 30MW and fire duration of 100 minuets. This information was used for all the cases. The parameter n was chosen as 2, in order to adjust the growth rate to linear rate. In figure 2, the results are shown.

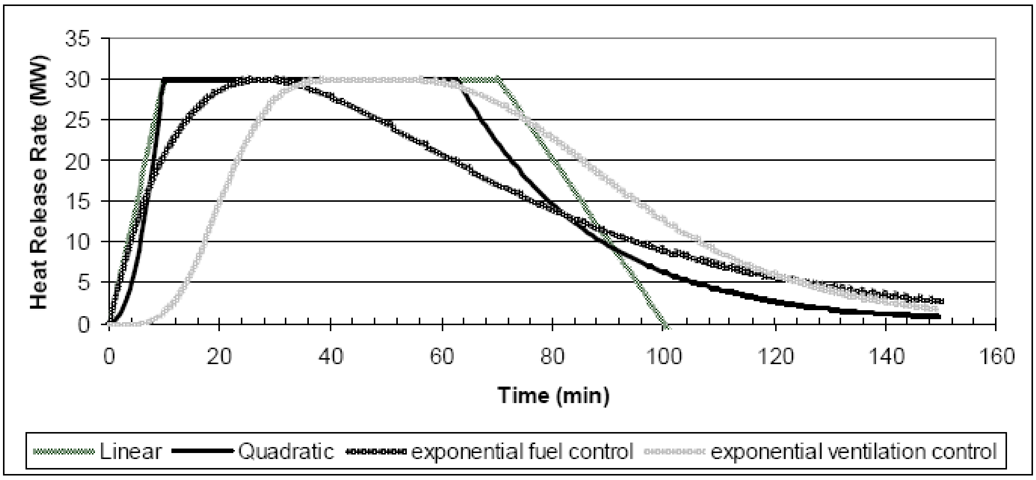

Figure 2: An example plotted for the HRR curves. The input was obtained from table 2, $E_{tot} = 144 GJ$ and $\dot{Q}_{\max} = 30 MW$; other parameter used where **linear**: $t_d = 100 \min$, $\alpha_{g,L} = 3 MW/\min$, $\alpha_{D,L} = 3 MW/\min$, **quadratic**: $\alpha_{g,q} = 0.3 MW/\min^2$ $\alpha_{D,q} = 0.042 MW/\min^2$, **exponential**: n=2, β_d=0.99.

The integrated area is the same for all curves. The exponential curves are more favourable to use since it gives a more realistic representation of a real fire curve.

Conclusions

Tunnels are one the most important public transportation systems, so fire in tunnels may be causing the considerable victims and damages. Thus, the consideration of the fire in tunnels is vital. In this research, mathematical models for representation of complete design fire curves were presented and a comparison was made among different methods. It is recommended to use the exponential representation using one single function since it gives more realistic shape of the fire curves. It is also robust and easy use.

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