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SPRINKLER ACTIVATION TIME IN A REDUCED SCALE CAR ROAD TUNNEL

Bogdan BRĂNIŞTEANU [1], Adrian RETEZAN [1], Ion ANGHEL [2]

[1] "Politehnica" University of Timişoara, Civil Engineering Department, 300222, Timişoara, Romania
[2] „Alexandru Ioan Cuza"Police Academy, Fire Officers Faculty, 022451, Bucharest, Romania
E-mail: `albulescugrig@gmail.com`

Abstract. There are important networks of road tunnels across the entire continent of Europe. Some of these tunnels are equipped with sprinkler suppression systems and smoke control devices. The effectiveness of sprinkler systems is influenced by the activation time and smoke control device properties. The aim of this study is to identify the interdependence criteria between sprinkler activation time and ventilation air flow in a reduced scale road tunnel.

Key words: sprinkler, road tunnel, response time index, reduced scale.

NOMENCLATURE

A	[m^2] – area of the sprinkler body
c	[J/kgK] – specific heat
C	[m/s]$^{1/2}$ – conductivity factor
h	[kw/m^{2}K] – convective heat coefficient
L	[m] – length scale
m	[kg] – mass of sprinkler body
Q	[Kw] – total heat release rate
t	[s] – time
T_a	[K] – ambient temperature
T_d	[K] – link temperature
T_g	[K] – gas temperature
T_m	[K] – temperature of the sprinkler mount
u	[m/s] – gas velocity
β	[–] – volume fraction of water in the gas stream
τ	[–] – time constant

1. INTRODUCTION

The road tunnels network represents the easiest way to connect the most important continental cities using the shortest route. It can cross the most inaccessible land zones in order to facilitate the access and economic trade. However, all these facilities could not be achieved without a reliable security system, even if we talk about traffic control systems or fire suppression systems. If fires occur in these systems it would cause not only material damages, but unfortunately, also injuries and loss of human lives. The most important method to control a tunnel fire until the firefighters arrive is represented by the use of a fire suppression system. Beside the fire suppression systems, some of these tunnels may have a smoke control system, and both systems can interact one with another. Fire safety engineers often face with similar situations and that is why research activities regarding this subject are very important. It is obviously that large scale experiments are the most accurate instruments to achieve realistic data about the fire development inside a tunnel, but they are more expensive than the reduced scale models. It should be stressed that reduced scale technique could be used to validate computational models or theoretical formulations.

2. METHODS AND MATERIALS

The reduced scale 1:10 road tunnel was built in the Fire Department Laboratory of the URBAN INCERC Institute in Bucharest. The tunnel was constructed from Promatect H boards with two layers of 15 mm thickness with 870 kg/m^3 density, 1 130 J/kgK heat capacity and 0.175 W/mK heat conduction. Dimensions of the tunnel were 7 m length, 0.64 m width and 0.56 m height. Three standard pendant sprinkler heads were placed inside the tunnel according to Fig. 1.

An electrical axial ventilator with variable speed was used to create the air flow conditions. Different longitudinal velocities of 1.2 m/s, 3 m/s and 6 m/s were used in the tests and measured with an anemometer.

Since the model tunnel was built on a scale of 1:10, a number of scaling correlations using the Froude method were applied to this experiment [1]. All the correlations are expressed in Table 1.

The fire load consisted of steel pans filled with two different combustible liquids to simulate a single car fire. Diesel fuel and ethanol were used in the experiments. The liquid fuels were ignited in a rectangular steel pan in order to obtain a 15 kW heat release rate. Recent studies have shown that a single car involved in a fire possess an average heat release rate of 5 MW [2]. Using the above scaling technique it was highlighted that the optimum value for heat release rate necessary for this experiment is 15 kW. To record the temperatures inside the reduced scale tunnel eleven type K thermocouples were placed alongside the ceiling and a thermocouple tree was positioned above the fire place.

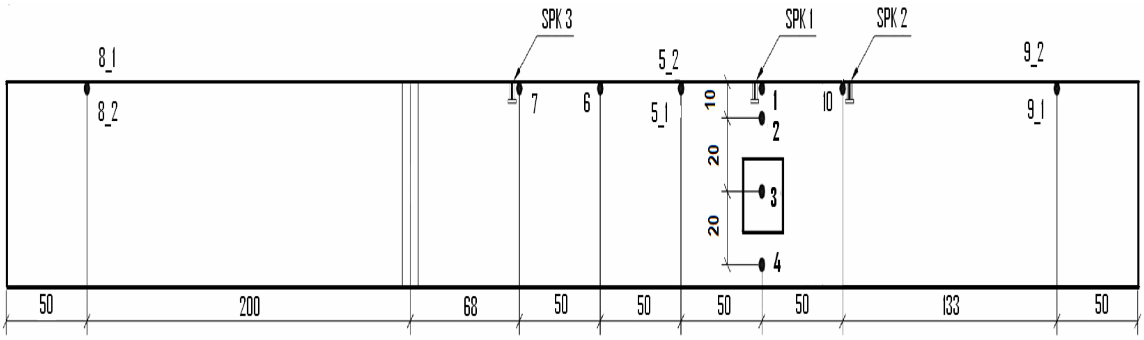

Fig. 1 – Sprinkler heads and thermocouples layout.

Table 1

Model scaling correlations [1]

Parameter	Scaling relationship	Number
Heat release rate (HRR) (kW)	$\frac{Q_F}{Q_M}=\left(\frac{L_F}{L_M}\right)^{5/2}$	(1)
Flow volume (m^3/s)	$\frac{V_F}{V_M}=\left(\frac{L_F}{L_M}\right)^{5/2}$	(2)
Velocity (m/s)	$\frac{u_F}{u_M}=\left(\frac{L_F}{L_M}\right)^{1/2}$	(3)
Time (s)	$\frac{t_F}{t_M}=\left(\frac{L_F}{L_M}\right)^{1/2}$	(4)
Energy (kJ)	$\frac{E_F}{E_M}=\left(\frac{L_F}{L_M}\right)^{3}$	(5)
Response Time Index (m$^{1/2}$s$^{1/2}$)	$\frac{RTI_M}{RTI_F}=\left(\frac{l_M}{l_F}\right)^{\frac{3}{4}}$	(6)
Temperature (K)	$T_F=T_M$	(7)

To calculate the response time index of sprinkler head, a differential equation including convective heating of the sensing element and conductive losses to the sprinkler frame is commonly used [3, 4]:

$$\frac{\mathrm{d}T_d}{\mathrm{d}t}=\frac{\sqrt{u}}{RTI}\left(T_g-T_d\right)-\frac{C}{RTI}\left(T_d-T_m\right)-\frac{C_2}{RTI}\beta u. \tag{8}$$

Assuming that the response time index (RTI) is:

$$\mathrm{RTI}=\frac{mc}{hA}u^{\frac{1}{2}} \tag{9}$$

and introducing a characteristic time t_0 and a characteristic temperature T_0, equation (8) can be:

$$\frac{\mathrm{d}\dot{T}_d}{\mathrm{d}\dot{t}}=\frac{\sqrt{u}}{RTI}t_0\left(\dot{T}_g-\dot{T}_d\right)-\frac{C}{RTI}t_0\left(\dot{T}_d-\dot{T}_m\right)-\frac{C_2}{RTI\cdot T_0}t_0\beta u. \tag{10}$$

Temperature and β have the same values in both scales according to table no. 1. The C_2 is known as Di Marzo constant, which is empirically determined to be 6×10^6 K/(m/s)$^{1/2}$ [5]. Substituting these two elements, three dimensionless terms are obtained:

$$\frac{\sqrt{u}}{RTI}t_0=\frac{hAt_0}{mc}=\frac{t_0}{\tau}=C_1 \tag{11}$$

$$\frac{t_0}{mc}=C_2 \tag{12}$$

$$\frac{u}{RTI}t_0=C_3. \tag{13}$$

The equations (11), (12), (13) represent in order the expressions for: the convective heat transfer, the heat conduction loss and the cooling effect of the bulb by water droplets in the gas flow. It must be pointed out that there are some limitations to consider on several parameters [6].

Using equations (3) and (4) to express velocity and time scales and assuming that in this experiment sprinklers have no water on the pipes and the heat conduction losses to the sprinkler frame are very small, we can ignore the C_2 and C_3 terms. As the heat transfer dominates the heat balance of the sensitive element, RTI is scaled as:

$$\frac{\mathrm{RTI}_M}{\mathrm{RTI}_F}=\left(\frac{l_M}{l_F}\right)^{\frac{3}{4}}. \tag{14}$$

It is hard to obtain a very small sprinkler bulb, especially because on the market are few specific producers. That is why all sprinklers used in experiments were the same type with a glass bulb having a 3 mm diameter and an RTI of 34 m$^{1/2}$s$^{1/2}$, corresponding to 191 m$^{1/2}$s$^{1/2}$ on a large scale. According to the international standards sprinklers having a thermal element with a RTI of 191 m$^{1/2}$s$^{1/2}$ are classified as standard response.

3. RESULTS AND DISCUSSION

The experimental results led to the following observations concerning the activation time:

Sprinkler head activation time increases inversely with the value of the ceiling temperature. Ventilation velocity influences the fire growth by decreasing the burning period and the ceiling temperatures. Information on Table 2 shows that the activation time of sprinklers decreases with the ventilation velocity of 3 m/s and above the value of 6 m/s no sprinkler bulbs were activated.

Upward ceiling jet temperatures represent the most important parameter regarding the activation time of sprinkler heads. This parameter is strongly influenced by airflow movement. The highest values of temperature were recorded by the thermocouple tree and tend to be similar in all the experiments using the same fuel. In all tests, the thermocouple no. 3 indicates peak values of temperature because it is placed inside the flames. When the ventilation speed is 1.2 m/s the ceiling temperatures are close to 200 ^{0}C corresponding to those achieved in real scale experiments [7]. The obtained temperature charts reveal some differences between time periods before the moment when temperatures reached the same value for every burnt fuel.

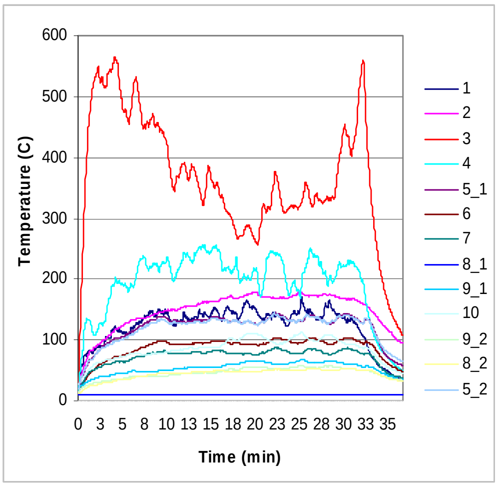

Fig. 2 – Ethanol burning with 1.2 m/s air velocity.

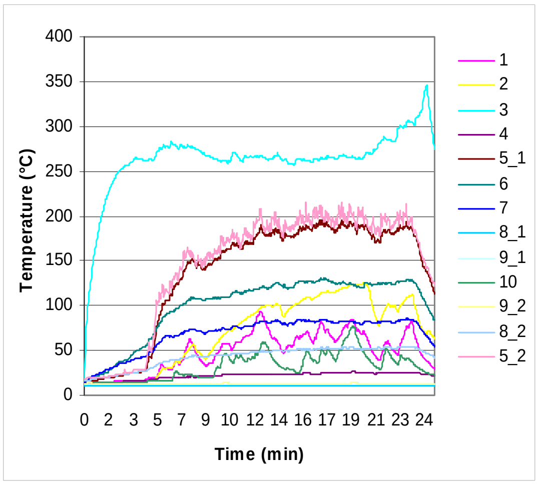

Fig. 3 – Ethanol burning with 3 m/s air velocity.

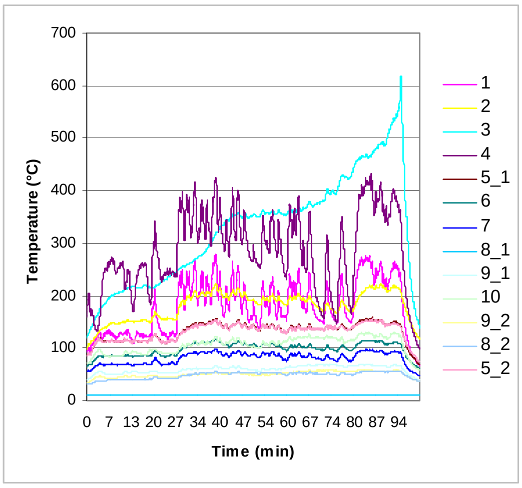

Fig. 4 – Diesel fuel burning with 1.2 m/s air velocity.

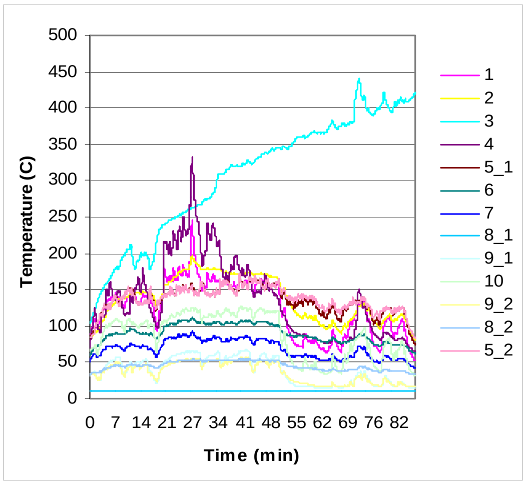

Fig. 5 – Diesel fuel burning with 3 m/s air velocity.

Table 2

Experimental results

Activation time (s)	Ventilation speed (m/s)					
	1.2		3		6	
	Fuel type					
	Ethanol	Diesel	Ethanol	Diesel	Ethanol	Diesel
Sprinkler no.	43	39	116	105	Not activated	
Sprinkler no.	102	93	270	242	Not activated	
Sprinkler no.	156	141	363	314	Not activated	

The response time of the sprinklers is influenced by the ceiling jet temperatures, which in turn depend on the fire load, heat release rate, the nature of the burning fuel and the position of the fire place. It can be observed in Figs. 6, 7 and 8 that fire generates the highest temperatures in the area around the fire pool. Information in Table 2 shows that between the two fuels used in the experiments there are important differences regarding sprinkler activation time since every fuel develops different temperatures during the combustion process.

Fig. 6 – Video camera image of fire place.

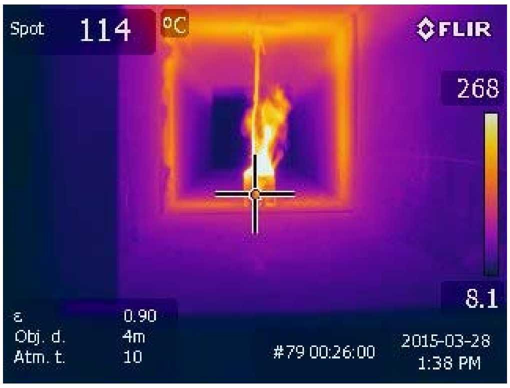

Fig. 7 – Thermal camera image of fire place.

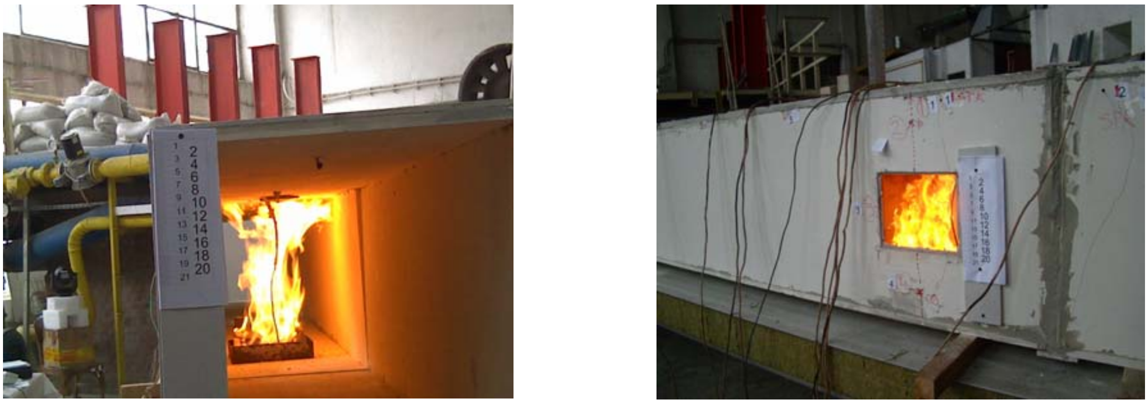

Fig. 8 – View of the reduced scale tunnel during the experimental test.

Based on the results, the cause of different sprinkler activation times seems to be a result of various burning fuels types in combination with the position of the fire source. It can be pointed out that air flow velocity influenced the burning rate and the quantity of fuel burned. Although the heat release rate has the same value for all the tests, the chemical composition of fuels leads to differences in burning temperatures.

4. CONCLUSIONS

First activated sprinkler glass bulb in all tests was the one placed in the vicinity of the fire source. When the velocity values of the ventilator exceeds 6 m/s the air flow cools down the ceiling temperatures enough so as none of the bulbs were activated, resulting in a collapse of the sprinkler suppression process. Oxygen enrichment caused by the air flow accelerates the combustion process decreasing burning period. The flames are angled by the speed of the air, increasing the possibility of the fire rapidly spreading from one car to another. In such a scenario, when more than one car is engulfed by flames, firefighting techniques are very hard to be implemented. If the ventilators are designed to start after first sprinkler activation, then the value of air velocity must be established in such a way that it will not influence the activation of other sprinkler bulbs. Experimental results indicate that sprinkler response time depends on the starting conditions and on the type of fuel in the burning pool. Fire safety engineers could design the appropriate fire suppression systems knowing the specific response time index of sprinkler thermal links. Sprinkler heads must be carefully chosen to achieve the required performance to extinguish a fire. The response time index and specific temperature are the most important parameters when designing a sprinkler system in a road tunnel. If local regulations or designers require a smoke control system in such applications, special consideration should be given to ventilator velocity in order to avoid the collapse of the fire suppression systems.

Experimental results suggest that the reduced scale tunnel model yields reliable burning temperatures and sprinkler activation time data.

It is hard to obtain accurate predictions of the activation time of sprinklers because in a real tunnel fire, the incidents can involve different categories of combustible materials and liquids, but reduced scale experiments could enhance research activities in the field of fire safety engineering and can offer valuable information to engineers to be used in the design stage of any project.

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