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EXPERIMENTAL INVESTIGATION ON THE CHARACTERISTICS OF FIRES IN A REDUCED 1/10 SCALE ROAD TUNNEL USING DIFFERENT COMBUSTIBLE LIQUID POOLS

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Abstract: *The article presents multiple 1/10 reduced-scale experiments using Froude scaling. These experiments were conducted in order to investigate to what extent the diesel, the gasoline and the ethanol can accurately produce the characteristics and the dynamics of a real automobile fire in a road tunnel. The article focuses on experiments (scaled 1/10) and calculation methods that can predict the value of the heat flux from a road tunnel fire (the Heat Release Rate – HRR). Application of the scaling method resulted in a 15 kW peak HRR for a reduced scale (1/10) automobile of 5MW. Also the dimensions of the rectangular fire pans were calculated, so as to feed such a peak value of HRR of 15 kW, with the three different liquid fuels. Validations of the experiments regarding the HRR were achieved by comparing the experimental values with calculated ones. The validation of the results regarding temperatures at the ceiling level above the fire was done by comparing the results obtained from reduced scaled experiments with the full scale experiments related values.*

Key words: *liquid pool fires, heat release rate, 1/10 reduced-scale, Froude scaling, mass loss rate*

1. INTRODUCTION

The statistics proves that the road tunnel fires are pretty rare when it comes to the total number of automobile fires or all building fires. Nevertheless, the road tunnel fires can bring disastrous consequences. For example, the Mont Blanc road tunnel fire in 1999 caused 39 deaths and left 30 people injured [1]; in Tauern road tunnel fire in 1999, 12 people were killed and 42 injured [2]; in Gotthard road tunnel fire in Switzerland 2001, 11 people were killed [3] and in Daegu, Korea in 2003, a road tunnel fire caused 198 deaths and 146 injures [4].

The above tragedies demonstrate that tunnel fires are still serious threats and thus we need to study and pay more attention to identify methods to prevent and fight these types of fires [5].

Large damages to the tunnel constructions result in high cost for refurbishment. In such big tunnel fires, concrete finishes over the steel reinforcement are spalled down. Indirect financial loss due to disturbing the normal traffic is large and difficult to estimate [6].

Romania has 9 road tunnels with a cumulated length of only 1.6 km, despite the fact that the country has a lot of mountains, and that would justify the need for more tunnels, but in the near future, the new highway to be built includes more complex tunnels. The longest tunnel we have at the moment is Capra-Bâlea road tunnel, situated on Transfăgărășan, with a length of 864 m [7].

Generally, a tunnel fire has a very complex flow structure because the geometry of the tunnel affects all physical phenomena, also affecting the way the ventilation system works [8]. Fire tests are of vital importance in understanding the fires applied physics in tunnels, in understanding the fire impacts, and for a proper verification of calculus, assumptions, and appropriate computer models and tunnels designs [9].

Full-scale tests [10, 11, 12, 13 and 14] are expensive and consist of complex tasks to be put into practice. They require access to a tunnel or to a full-scale mock-up with some basic installations. There are some aspects of the experiments which are difficult to control such as natural ventilation (wind) conditions. For example, the Heat Release Rate data gathered from the Runehamar tunnel full scale fire tests have a 15 – 20 % uncertainty [11, 15].

Small-scale experiments can be designed to represent a fire in a planned environment. This method is based on similarity laws, which are actually the link between a full scale situation and the modelled one. Reduced scale tests are not affected by natural factors such as winds, elevations and solar radiation, and can be repeated as many times as necessary. Also in such tests, smoke is easily observable [9].

So far, numerous tests were done in reduced scale tunnels: 1/6 reduced-scale tunnel [16]; 1/9 [5]; 1/10 [17]; 1/15 [18, 19]; 1/20 reduced-scale tunnel [20, 21] and 1/30 reduced-scale tunnel [22]. During the past few years, a series of theories and models for liquid pool tunnel fires have been developed by experiments using as fuel only one combustible liquid: methanol [5, 8, 17, 23, 19], kerosene [23], ethanol [20] and heptane [16, 21, 19, 22].

In tunnel fire studies, the HRR and temperature distribution is often an important aspect of the research [5, 6, 8, 10, 11, 12, 13, 18, 24].

All studies in the area of tunnel fire safety are helpful to understand the idea of pool fires in the relatively narrow space of a tunnel, providing solutions for tunnel fire-fighting systems design [5].

In the design stage the Heat Release Rate is calculated in order to estimate the fire growth and the temperatures that can be reached.

In this article, the 1/10 reduced-scale experiments using Froude scaling are conducted in order to investigate the ability of diesel, gasoline and ethanol to reproduce the most appropriate characteristics and dynamics of a car fire in a road tunnel.

The test results obtained from scaling model were compared with large-scale test results in order to determine the maximum combustion efficiency for each liquid fuel in relation with studied parameters, involved in the complex dynamics of road tunnel fires.

2. THEORETICAL AND EXPERIMENTAL MODEL

To experimentally determine the rate of heat release (HRR), two methods are widely used.

First method and the most known is cone calorimeter method, by using the oxygen consumption. Heat Release Rate is then calculated using the relation between the released energy and the consumed oxygen.

Because there are limitations when using cone calorimeter method, as an alternative method, Heat Release Rate (HRR) is measured based on mass loss rate, using high precision equipment. This method uses the time dependent mass loss rate measured from experiment and calculates the Heat Release Rate with equation 1 [25].

$$\dot{Q} = \chi \Delta h_C \dot{m}'' A \qquad (1)$$

Nomenclature for all equations is situated at the end of this article.

For pool fires that may occur in a road tunnel, the conservation energy that can be applied to a fire pool is:

$$\dot{q} = \dot{q}''A = (\dot{q}''_r + \dot{q}''_C - \dot{q}''_{rr} + \dot{q}''_{loss})\left(\frac{\Delta h_c}{\Delta h_g}\right)A \qquad (2)$$

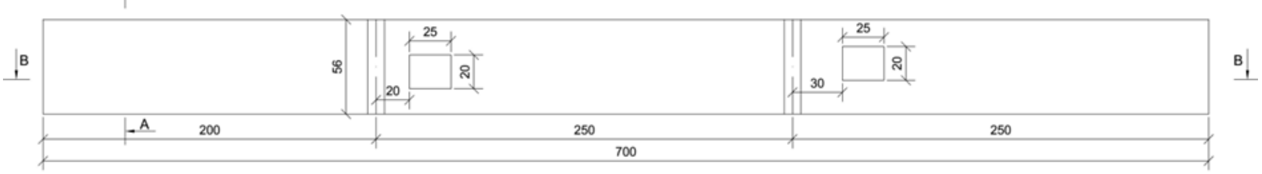

Fig. 1. Side view of tunnel model

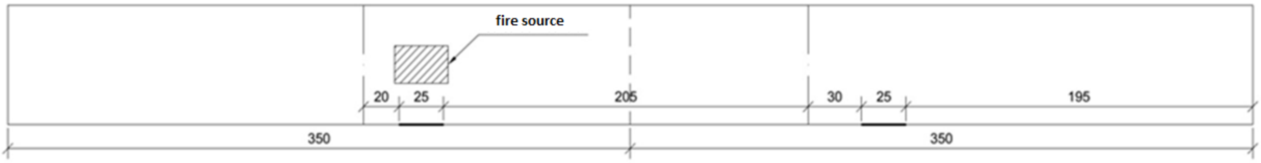

Fig. 2. Top view (Section B-B) of tunnel model

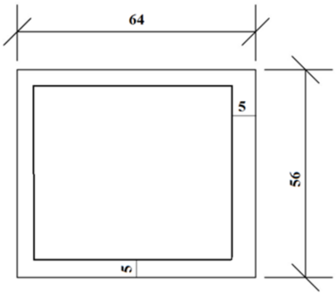

Fig. 3. Section A-A of tunnel model

The reduced scale 1/10 road tunnel was built in the Fire Department Laboratory of the URBAN INCERC Institute in Bucharest.

Since the model tunnel was built on a 1/10 scale, a number of scaling correlations using the Froude method were applied to this experiment [26]. All the correlations are expressed in Table 1. In figures 1, 2 and 3 is shown the tunnel layout (section and elevation).

Figure 4 presents a part of the reduced scale tunnel in which are pointed out the instrumentation, data analysis units and glass surfaces.

Fig. 4. Reduced scale tunnel model during experimental test (gasoline pool fire)

The fire load consisted of steel pans filled with three different combustible liquids to simulate a single car fire.

A series of tests were conducted in the 1/10 reduced-scale tunnel, as shown in figure 4.

The tunnel model was built from non-combustible materials with two layers of 15 mm thick Promatect H boards, with 870 kg/m^3 density, 1130 J/kg K heat capacity and 0.175 W/m K thermal conductivity [7]. Overall dimensions of the scaled tunnel: length – 7.0 m, width – 0.64 m and height – 0.56 m. The large scale tunnel dimensions are length – 70.0 m, width – 6.4 m and height – 5.6 m. The details of the experimental set-up have been also presented in [27] as shown in figures 1, 2, 3 and 4.

Table 1

Model scaling was achieved using Froude scaling technique [30].

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)	$\frac{V_F}{V_M} = \left(\frac{L_F}{L_M}\right)^{1/2}$	(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)
Mass (kg)	$M_F = (L_F)^3$	(6)

Two fire resistant glass windows (500 mm^2) were placed on the front wall of the tunnel to allow observation of the fire growth from the outside.

According to the real scale tests, a single car specific Heat Release Rate (HRR) was established to roughly 5 MW, results obtain by repeated burning tests of different sized cars [28]. The time to reach the peak Heat Release Rate is situated between 10 and 55 minutes.

Diesel fuel, ethanol and gasoline were used in the burning experiments done into the 1/10 scale tunnel. These fuels were burned in rectangular stainless steel pans with different dimensions for each liquid in order to obtain a 15 kW Heat Release Rate (HRR), as shown in table 1 (shape of pan is rectangular in order to physically simulate a car shape with a uniform distributed fixed mass).

A reverse order calculation method was adopted, starting with the required HRR equivalent to a 1/10 scale car model and then applying the Froude scaling procedure.

A value of 15.81 kW (approx. 15 kW) has resulted, which represents roughly that the Heat Release Rate for a modern car is 5 MW.

The burning characteristics for these three fuels are shown in table 3.

Pool combustion was initiated at ambient temperature using a propane gas burner.

The fuel mass loss rate was determined by the rate of vaporized gas leaving the pool.

Table 3

Thermal properties for liquid fuels.

Fuel	**Mass burning rate m” (kg/m²s)**	**Heat of combustion ΔH_c (kJ/kg)**	**Density ρ (kg/m³)**	**Empirical constant $k\beta$ (m⁻¹)**
Diesel	0.045	44400	918	2.1
Ethanol	0.015	26800	794	100
Gasoline	0.055	43700	740	2.1

A KERN load cell was placed under the pan at 0.455 m far away from the left entrance of the tunnel. This weight assembly was used to measure the fuel consumption in the time period. To estimate HRR of the fuel placed inside the fire compartment, several equations were used. Hottel’s analysis showed that two basic regimes are possible on liquid pool fires: radiative burning for large pool fires and convective burning for small pool fires [25].

In the radiative regime, organic liquids have a HRR that can be correlated by:

$$\dot{Q} = \Delta h_C \dot{m}''\left(1 - e^{-k\beta D}\right)A \qquad (3)$$

Pool fire diameter can be calculated following equation 4:

$$D = \sqrt{\frac{4A}{\pi}} \qquad (4)$$

The temperature distributions are measured by K-type thermocouples in order to investigate smoke movement. Layout of the thermocouples is presented in figure 5.

The rectangular steel pans dimensions were carefully designed in order to ensure the same energy release for the three liquid fuels.

The pan size actually represents the most important parameter which directly affects height of the flames and burning duration.

Table 2

Dimensions of fire pans for 15 kW HRR.

Type of fuel	**Pan dimensions**		
	Length	Width	Height
Diesel	0.25	0.10	0.10
Ethanol	0.37	0.10	0.10
Gasoline	0.17	0.10	0.10

3. RESULTS AND DISCUSSIONS

According to fire exposure conditions, type of fuel and data collected, the experiments were divided into two categories as follows:

- first three tests were orientated on assessing the Heat Release Rate from liquid fuels using mass loss rate procedure;
- next three tests aimed to produce results regarding fire development (figure 4 for gasoline pool fire) and fire behaviour in a road tunnel (temperatures, smoke layering and flame height).

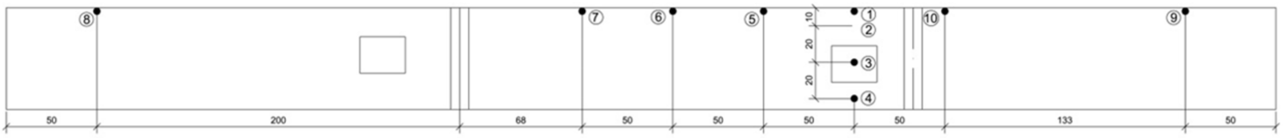

Fig. 5. Thermocouples layout

In order to obtain a global view on the results for each liquid fuel tested a comparison between effective mass loss rate is shown in figure 6.

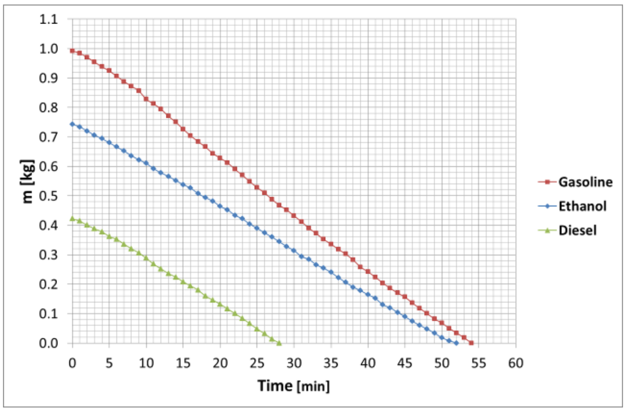

Fig. 6. Effective mass loss rate as a function of time, recorded during tests

Heat Release Rate calculations were done using following equations:

$$HRR = \dot{Q} = \frac{m\Delta H_{eff}}{\tau} = \frac{m\gamma}{\tau}\Delta H_{eff} \qquad (5)$$

$$\dot{Q} = \Delta h_c \cdot A \cdot \dot{m} \qquad (6)$$

The HRR obtained for all three liquid fuels after the experimental tests are presented in figure 7.

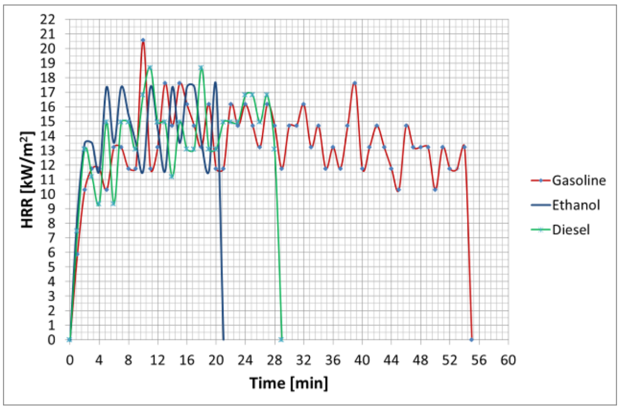

Fig. 7. Heat Release Rate for ethanol, gasoline and diesel fuel pans

Based on the tests results following conclusions can be highlighted:

- from free burning tests made to determine the Heat Release Rate based on mass loss rate procedure, their peak values of 17 kW were obtained for ethanol fuel, 18.2 kW for diesel and 20.2 kW for gasoline;
- good agreement was found between measured average Heat Release Rate with values between 13.49 kW for ethanol and 13.69 kW for gasoline;
- average mass loss rate per time unit recorded was similar among the types of fuels used with values ranging between 0.016 kg/min for ethanol and 0.021 kg/min for gasoline;
- complete burning time for the liquid fuels has been 20 minutes for ethanol, 28 minutes for diesel and 54 minutes for gasoline.

Experimental results are reasonably good, being within 5 % of the calculated method and they tend to be conservative for all types of fuel used in tests. These differences may occur from multiple influences such as errors (mainly measuring) and assumptions (like assumed instantaneous combustion).

The ceiling (the profile of temperatures on the ceiling for each combustible liquid case) maximum thermal smoke temperatures inside the tunnel obtained for all three liquid fuels after the experimental tests are presented in figures 8, 9 and 10.

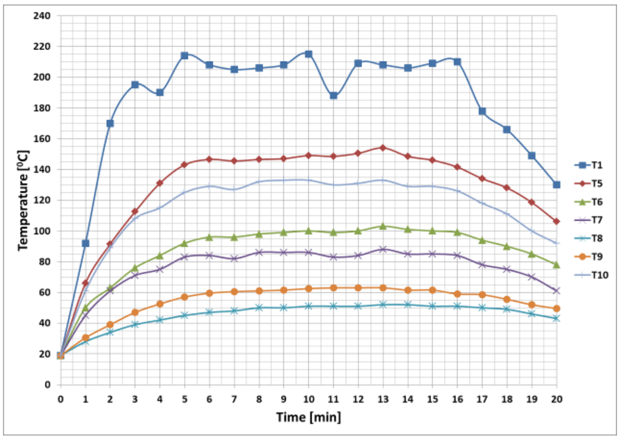

Fig. 8. Temperature distribution inside the tunnel for gasoline fuel pan

The mathematical model for smoke layer temperature prediction inside the tunnel proposed by Li [24] and later confirmed by Tang [29] is consistent with the experimental results considering the fire source in the middle of tunnel:

$$\Delta Tmax = \begin{cases} \dfrac{Q}{ur^{1/3}H_d^{5/3}} & u' > 0{,}19 \\ 17{,}5\,\dfrac{Q^{2/3}}{H_d^{5/3}} & u' \lesssim 0{,}19 \end{cases} \qquad (7)$$

$$u' = \frac{u}{(\frac{Q_c g}{r \rho_a c_p T_a})^{1/3}} \qquad (8)$$

In large scale road tunnel fire tests peak ceiling gas temperature in the vicinity of the source for a single car tends to be close to 210 °C, as shown in Second Benelux test [10].

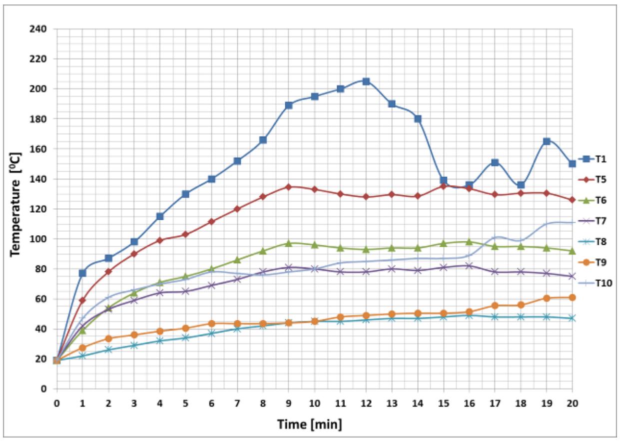

Fig. 9. Temperature distribution inside the tunnel for ethanol fuel pan

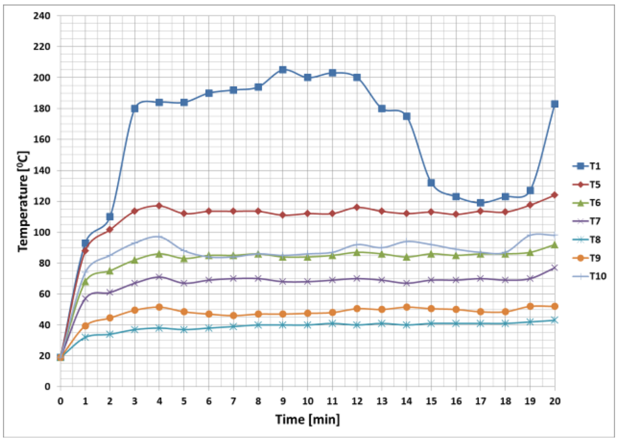

Fig. 10. Temperature distribution inside the tunnel for diesel fuel pan

In figures 11-17 the temperature values in the seven points on the center of ceiling (fig. 5) are presented. The order of the thermocouples on the graphs is established based on the distance from the vertical axis from center of the pan. (T1 - above pan, T5 - 50 cm away from pan on the left side, T10 - 50 cm away from pan on the right side, T6 - 100 cm on the left side, T7 - 150 cm left side, T 9 - 183 cm right side and T8 - 418 cm away from fire pan, left side.

Values obtained by T2,3 and 4 thermocouples are not subject of this research (as being flame temperatures).

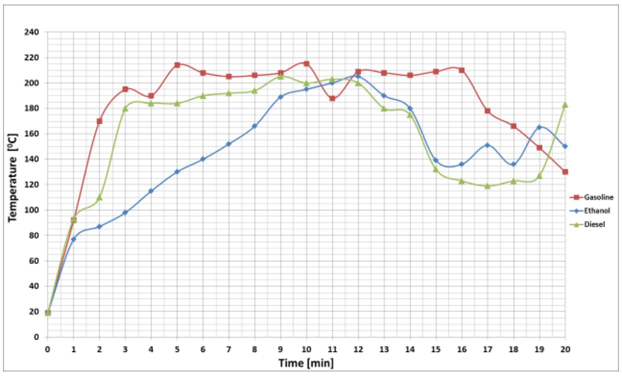

Fig. 11. Temperature comparison in thermocouple T1 for gasoline, ethanol and diesel fuel pans

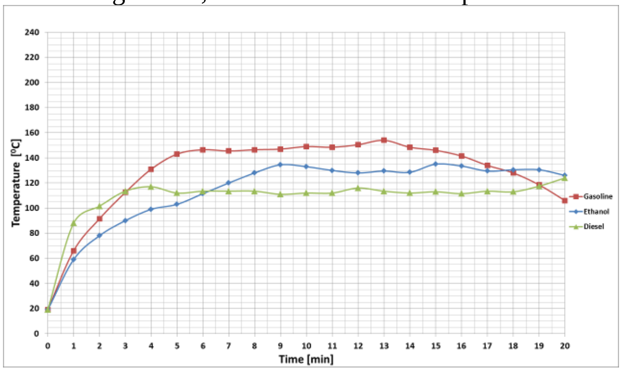

Fig. 12. Temperature comparison in thermocouple T5 for gasoline, ethanol and diesel fuel pans

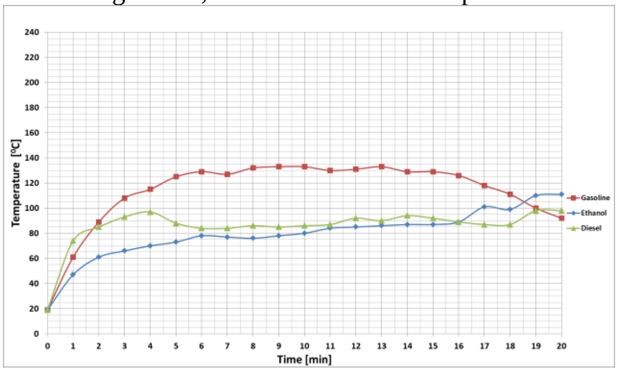

Fig. 13. Temperature comparison in thermocouple T10 for gasoline, ethanol and diesel fuel pans

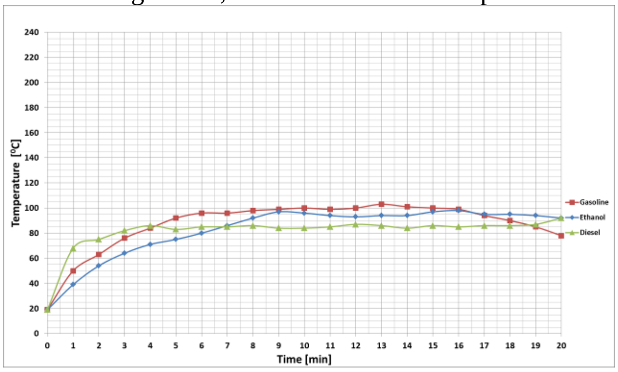

Fig. 14. Temperature comparison in thermocouple T6 for gasoline, ethanol and diesel fuel pans

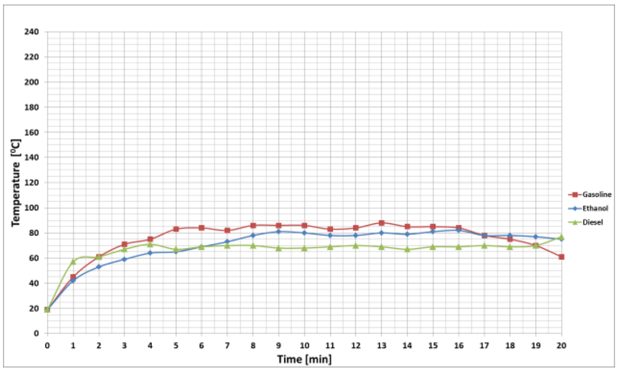

Fig. 15. Temperature comparison in thermocouple T7 for gasoline, ethanol and diesel fuel pans

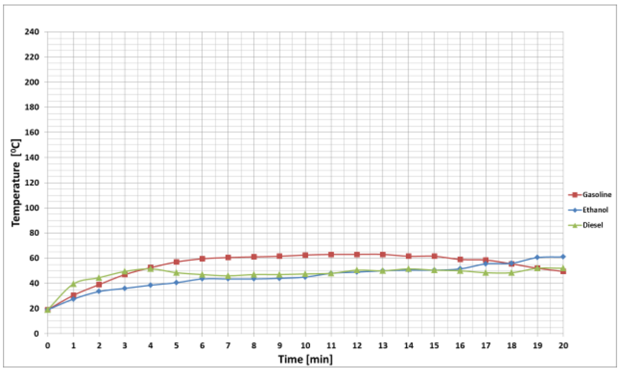

Fig. 16. Temperature comparison in thermocouple T9 for gasoline, ethanol and diesel fuel pans

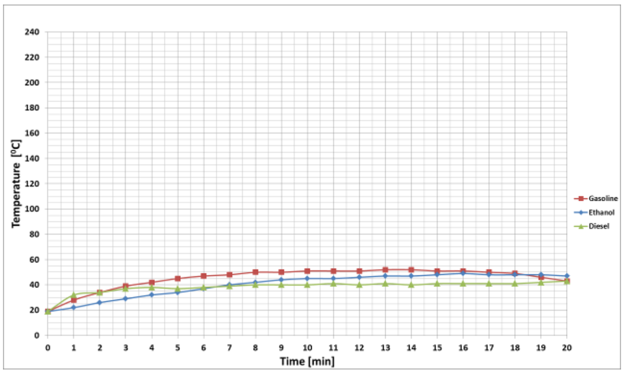

Fig. 17. Temperature comparison in thermocouple T8 for gasoline, ethanol and diesel fuel pans

As expected, temperatures drop with distance of thermocouple away from burning pan in both directions (there is no forced ventilation).

Largest temperatures in smoke are read in T1, above burning fire pan. Also the biggest temperature fluctuations are identified same with T1, because of the accessional intermittent air flows generated by the fire plume of the fire pool.

Temperatures in the upper region of the tunnel increase with time because the smoke of the high temperature that generated in the fire source moves along the ceiling of the tunnel.

The ceiling gas temperature is directly related to the pattern of smoke flow in tunnel. When a fire occurs, the plume rises and spreads radially outward over the ceiling and then it reaches the corner formed by the sidewall and the ceiling and turns downwards along it. However, since the wall flow is at a higher temperature than that of the ambient surroundings, it is subjected to an opposing buoyancy force and the wall flow is thus termed negatively buoyant wall jet as depicted in [30].

The recirculating hot smoke accumulated beneath the ceiling cause the increase of ceiling gas temperature.

The ceiling gas temperature depends not only on the HRR of fire source but also on the tunnel geometry.

The temperature distribution inside the tunnel in case of diesel and gasoline fires tends to be close to the large scale results obtained [10].

Ethanol pool fire temperatures are smaller than large-scale fire tunnel tests results because alcohol fuels show minimal radiative flux in comparison to other fuels.

Froude equations have been proved to be able to correlate all the tests data in different scales very well.

4. CONCLUSIONS

Reduced-scale model for estimating Heat Release Rate in case of a pool fire in car road tunnels show that results obtained after experimental tests are close to the results obtained through the calculation method.

In order to obtain good accurate results, the research centred on two directions: complex specific rates (HRR) and the fire behaviour (temperatures and smoke layer dispersion). By taking into consideration the implications and burning properties of each fuel, the following findings were reached:

- the dimensions of the pans to be used in such tests need to be thoroughly calculated in order to properly simulate the HRR for every type of fuel. If one will use arbitrary chosen pans, large errors will occur regarding the temperatures and the burning duration;
- in the first stage of experimental studies, the recommended fuel is ethanol, as it favours a

direct observation – smoke is not produced when burning ethanol – and it is also environment friendly;

- as it gives a lot of smoke when burning, diesel would be the best choice when the intention of the test is to study the phenomena related to smoke production;
- in order to study the worst case scenario – thermally speaking – the recommended fuel is gasoline, as it burns with the highest temperatures (in comparison to other two fuels).

We can conclude that the results using the time dependent mass loss rate measurement to determine the HRR is reasonably good being in a 5 % error range.

The results validate the theoretical formulations to determine the burning rate of liquids in a pool fire inside a tunnel.

The distribution of the temperature values inside the tunnel in case of diesel and gasoline fires tends to have values that are close to the values obtained at large scale tests, especially when considering the fire source in the middle of the tunnel.

5. NOMENCLATURE

$\dot{Q}$, q - heat release rate, kW;
χ - factor for incomplete combustion < 1;
$\dot{m}''$ - mass burning rate, kg/m^{2}s;
$\dot{q}''_r$ - the radiant heat flux absorbed by the pool;
$\dot{q}''_C$ - the convective heat flux to the pool;
$\dot{q}''_{rr}$ - the heat flux reradiated from the surface of the pool;
$\dot{q}''_{loss}$ - wall conduction losses and nonsteady terms;
Δh_g - heat of gasification, kJ/kg^{-1};
Δh_C - heat of combustion, kJ/kg;
kβ - empirical constant, m^{-1};
D - diameter of pool fire, m;
$\Delta Tmax$ - maximum thermal smoke temperature below the long and narrow tunnel ceiling, °C;
r - the equivalent radius of fire source;
Q_c - convective heat release rate (convective HRR) of the fire plume, kW;
ρ_a - the ambient air density, kg/m^3;
u - the longitudinal ventilation velocity, m/s ;
c_p - air specific heat at constant pressure;
T_a - the ambient temperature, °C;
H_d - the vertical height between the fire source and the tunnel ceiling, m;
u' - dimensionless longitudinal wind speed.

6. ACKNOWLEDGEMENTS

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Investigații experimentale cu privire la caracteristicile incendiilor într-un tunel redus la scara 1/10, folosindu-se ca surse de incendiu diferite lichide combustibile

În acest articol, se prezintă experimente de ardere la scară redusă 1/10, în care s-a folosit modelarea după criteriul de similitudine Froude pentru a verifica în ce măsură motorina, benzina și etanolul pot reproduce cât mai precis caracteristicile și dinamica unui incendiu de autoturism într-un tunel rutier. Articolul de față se concentrează pe metode de calcul matematic și metode experimentale (la scara 1/10) care pot previziona valoarea fluxului termic degajat de la un incendiu (eng: HRR – Heat Release Rate) izbucnit în interiorul unui tunel rutier. Conform teoriei scalării, a rezultat o valoare medie de 15 kW (considerând că, la scară reală, valoarea medie a HRR pentru un vehicul modern este de 5 MW). De asemenea s-au calculat dimensiunile tăvilor rectangulare pentru a asigura același HRR pentru cele trei lichide combustibile. Rezultatele privind fluxul termic degajat (HRR) obținute de la experimentele reduse la scară s-au validat prin compararea între ele a valorilor rezultate experimental cu valorile calculate. Validarea rezultatelor privind temperaturile de la nivelul plafonului de deasupra focarului s-a obținut prin compararea datelor obținute prin experimentele reduse la scară cu cele de la teste experimentale la scară reală/ naturală.

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