CONSIDERATIONS ON THE WAY TO DUPLICATE THE NATO STANDARD LIQUID FUEL FIRE FOR THE FAST COOK OFF (FCO) TEST

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ABSTRACT

The Fuel Fire Experts (FFE) working group has accomplished a great work for five years in order to propose an alternate method to do fast heating tests by using propane gas burners. The aim has mainly been to show how fuel gas fires could mimic the standard kerosene pool fire and in such a manner how they could be normalized. During this period French works have provided both numerical and experimental data in the Fast Cook Off debate.

From a fluid mechanical point of view, the liquid pool fire results in a large scale turbulent and vertical gas flow which engulfes the tested item during the FCO tests depicted by the STANAG 4240. As far as heat transfer is concerned, heat flux is mainly controlled by radiation of the very sooty flames. However gas burner flames result in more complete combustion and significantly produce less soot particles. The thermal boundary conditions of the tested item are thus affected.

French numerical approach has pointed out the great influence of some parameters on the thermal load produced by liquefied or not Gas fires. Burning rate of propane droplets, distance between test item and burner, and orientation of nozzles must be adjusted to mimic the heat transfer produced by the kerosene pool fire. Calculations have been made by using the Fire Dynamics Simulator (NIST software, USA) to directly compare the thermal boundary conditions produced by the different test facilities: the standard kerosene pool and the liquid propane gas burners (German-type and US-type).

Numerical results have been confirmed by experimental data presented by the US team which have showed the temperature and heat flux ranges we could expect within the different FCO test facilities (USA, Germany, Sweden…). In the same way, incident heat flux measurements have been made by the French two-paired thermocouple method and have been in good agreement with the US results and the calculated values.

All this collected data has been used to better characterize both kerosene pool fire and (liquefied or not) gas fires. The final purpose is still to standardize the alternative way to do fast heating for IM issues. Thus the alternate facility shall be designed to be compliant with the assessment of tested item from the smaller ammunitions to large solid rocket motors.

INTRODUCTION

Nowadays liquid fuel fire still remains one of the most realistic threats that can appear during the whole life cycle of the munitions. This thermal stimulus may occur either in storage buildings, or into ship magazines or even in overseas operations grounds.

The standard liquid fuel fire as defined by the current STANAG 4240 ed.2 is depicted as a large scale kerosene pool fire in which the tested munitions is engulfed [1-2]. In the standard document, requirements on flame tempatures are detailed to insure that munitions is fastly heated until it reacts. However it is also one of the most difficult threats to be tested and to be experimentally reproducible due to windy conditions. The flame plume may be deviated what it makes the item partially engulfed into the flames. On the other hand it also provides very sooty and optically thick flames. Radiation into the gas-particle media is mainly controlled by soot production from the uncomplete combustion of the large scale kerosene pool. Thus the resulting large dark plume dispersed further above the test facility makes some nations to stop using liquid kerosene pool. Sweden and Germany have been the first nations to propose the gas (liquified or not) as an alternative fuel to do FCO tests [3-4]. Then the Dutch and the US teams have suggested their own test facilities [5-6]. In face to the development of such new ways to do fast heating it has been necessary to demonstrate the capacity of the gas fires to mimic the standard liquid kerosene fire.

Many NATO Fuel Fire Expert Meetings have been hold from 2010 to 2015 where the works in progress of every nation have been presented. Many experimental efforts have been made first to characterize the standard liquid kerosene fuel fire. Then the thermal load has been measured around the munitions by using the alternative gas fire test facilities. The comparison of experimental results has showed what level of local thermal stimulus we can expect within every gas fire test setup [7]. However feedback with this kind of test facilities is still limited. Most of the comparative tests have been made without munitions and the influence of experimental metallic support has not yet been evaluated. Moreover experimental results may be limited by the capacity of sensors to measure continuous heat flux during the whole test duration.

That is why numerical efforts have been simultaneously made to point out the effects of the main experimental parameters (munitions support system, nozzle location, injection flow rate,…). Unlike the standard and uncontrollable liquid kerosene pool fire, the gas can be adjusted to provide satisfying thermal loads all around the munitions without any hot spots. That makes it difficult to be standardized and still remains the central point to be discussed by the IM community.

DESCRIPTION OF THE STANDARD LIQUID KEROSENE POOL FIRE

Before assessing the different gas fire test facilities it is necessary to describe what the standard fire is and what thermal stimulus it is able to provide towards the tested munitions. According to the STANAG 4240 ed.2 the main procedure to do fast heating requires the use of a large liquid kerosene pool that must engulf the whole tested item. That means kerosene vapours resulting from kerosene evaporation at the pool surface react with ambient air. As far as large pools are concerned combustion is very incomplete and yields gas temperatures lower than the adiabatic flame temperature. As mentioned by Blinov et al. [8], gas flow into large scale pool fires is pretty turbulent and instantaneous gas temperature varies from 300℃ to 1100℃ into the hearth. Regression rate depends on the kerosene type and is in the order of 5 mm/min. The mass flow rate of a burning 6m x 6m pool of liquid kerosene is typically around 0,068 kg/m²/s and the total heat release is more than 37 MW when the efficiency factor χ is set to 0,35 as usual for hydrocarbon fuels. As a result the gas temperature is spatially non uniform around the munitions. This is a function of the height above the pool surface and a maximum value is reached into the flames at a given distance above the pool surface (more than 0,3 meter as required by the STANAG 4240). Schematically if the tested munitions is perfectly engulfed into the hearth gas temperature can oscillate from 800℃ to around 1100℃ into the flames. But temperature is drastically decreased when the plume limit (where ambient air and burnt gas are mixed) is achieved.

The hearth is mainly composed of gas and particles produced by the incomplete combustion of kerosene pool. The main products are H_2O, CO_2, CO and soot particles, species typically induced by hydrocarbon fuel combustion. Diameter of the latter ones can vary from 0,01 µm to 1 µm whether they are agglomerated or not [9]. The agglomeration of soot particles has been particularly studied in order to assess both their toxicity and their thermal properties [10]. Smokes are indeed of great interest when toxicological effects and fire spreading are concerned. It is particularly true in the present study where heat transfer between flames and the tested munitions is mainly controlled by soot particles radiation. The flames of large scale kerosene pool fires are optically thick due to the huge soot production (Fig.1a) and the munitions is mainly heated by radiation of the hot gas-particle media produced all around.

Gas flow velocity into the flames is typically less than 20 m/s and convective transfer is pretty lower than radiative one. On the other hand deposit of soot particles may occur on the tested item during the test duration what directly affects the munitions emissivity and so on the munitions heating. As a result the radiative heat flux is conducted by soot and gas radiation. It varies from 40 up to 300 kW/m² and strongly depends on the location into the turbulent reactive gas flow [11]. In the vicinity of the tested munitions it has been continuously measured by the two-paired thermocouple method and is still in the 140-170 kW/m² range during the FCO test applied to a Solid Rocket Motor [2].

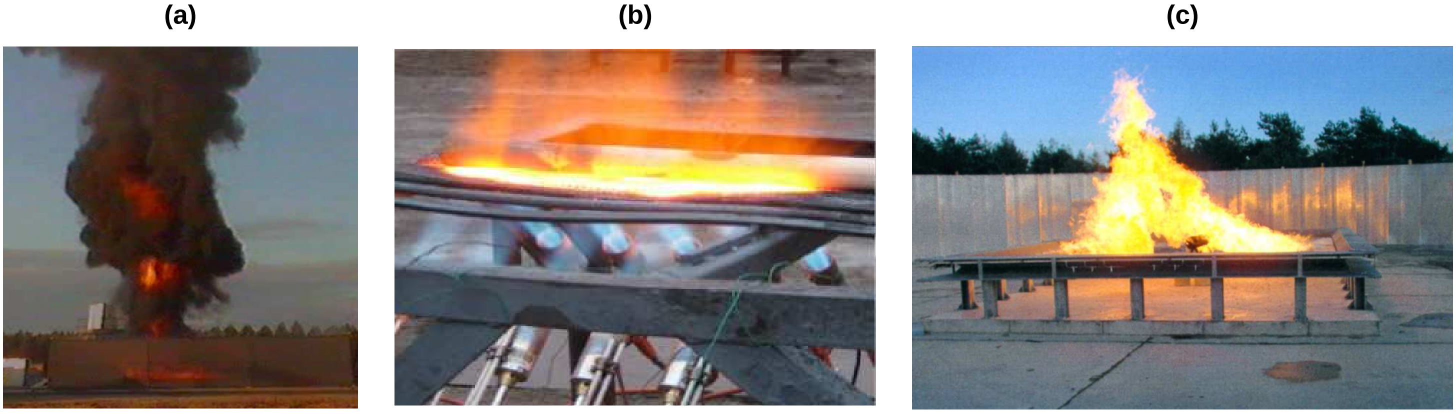


Figure 1 : Standard (a) and alternative (b-c) fire test setups to do fast heating [2-3-4]

DESCRIPTION OF THE (LIQUIFIED OR NOT) GAS FIRES

As far as the gas burners such as proposed by Sweden [4] and the Netherlands [5] are concerned a premixed gas propane (or butane) – air flame is formed to directly heat up the tested munitions (Fig.1b). Fuel and air gases are injected by all the burners maintained around the item. The ignition can be made by an electrical spark and the air/fuel mixture ratio must be calibrated to obtain not too high gas temperatures. Indeed if the fuel gas combustion is too complete, flame temperature can reach more than 1300℃ and be very different from the standard thermal stimulus. Besides the premixed gas/air fire is optically very thin since the tested munitions can be perfectly seen during the whole test duration. It could be an advantage to distinguish the reaction location but it actually shows how different the radiative properties of the kerosene pool fire and the premixed gas fire are. Inside the premixed gas fire flames are pretty less sooty and heat transfer is conducted by gas radiation and convection. The gas velocity is directly a function of the fuel flow rate and the nozzle type and can reach a large range of values. Most of the burners (or nozzles) are oriented towards the tested item and convective transfer can be predominant in comparison of the radiative part, particularly if fuel flow rate is high. Notice that the gas flow regime observed within this setup also depends on this parameter.

The test facility proposed by Germany is quite different since it is based on the injection of liquefied propane gas all around the munitions (Fig.1c) [6]. Unlike the Dutch setup a spray of liquid propane droplets is dispersed in the transversal axis by many nozzles maintained at a given distance from the item. The ignition can be made by an electrical spark or another system but the combustion process is very different from the gas and the kerosene pool fires. Here the diffusion flame results from the combustion of propane droplets with the ambient air. It is typically governed by the droplet combustion d^2-law (Eq.1). The resulting flames are function of the dispersion and the volume fraction of droplets and can engulf the whole tested munitions. Gas temperature can reach more than 1000℃ in the vicinity of the munitions but radiative properties are still different from burners and kerosene pool [3]. Liquified propane gas flames are optically thinner than kerosene pool fire ones but thicker than burners ones. The propane-air ratio and so on the soot production can directly be controlled by the droplet flow rate that is injected in the hearth. The effect of this parameter will be discussed in the further part.

$$d^2(t) = d_0^2 - kt \qquad \text{(Eq.1)}$$

where k, knwown as the constant burn rate, is a function of droplet density ρ_d, Spalding transfer number B, Sherwood number Sh.

At the end the last type of gas fire test facility is the American one proposed by Hubble et al. [6]. Unlike the German-type setup, gas propane is injected in the vertical axis by many ramps of pressurized fuel injectors in order to mimic the vertical gas flow induced by the standard kerosene fire. All the injection ramps are around 1 meter below the tested item and flames result from the gaseous reaction between propane vapours and ambient air. The observed flame plume looks like the kerosene pool one and the temperatures measured around the munitions are in accordance with the standard requirements. As made with the other facilities the fuel flow rate can also be adjusted to obtain more or less optically thin flames. But Hubble et al. have demonstrated the effect of metallic plates maintained all around the test setup. They limit the air flow rate and thus allow to provide optically thicker flames with a higher soot volume fraction. Radiative properties of such a fire may be similar to the standard kerosene ones.

However calibration and adjustments of all the gas fire test facilities are needed to get satisfying results. That is why the further part is focused on the influence of the main adjustable parameters on the thermal load seen by the munitions.

MODELING OF THE STANDARD AND ALTERNATIVE THERMAL LOADS

The first objective of the numerical approach is to compute the real liquid fuel fire that is the standard thermal stimuli of Fast Cook Off tests. The Fire Dynamics Simulator (FDS), software developed by the National Institute of STandards (NIST, USA) [12] and typically applied to civil fire safety issues, is used to calculate the kerosene pool fire. An approximate form of the Navier-Stokes equations appropriate for low Mach number applications is used in the model. The approximation involves the filtering out of acoustic waves and allows large variations in temperature and density. The computation is treated as a Large Eddy Simulation (LES) in which the sub-grid scale dissipative processes are modelled. The combustion of the liquid kerosene pool is taken into account by:

- calculating the evaporation rate of liquid kerosene above the pool surface when burning; according to the Clausius-Clapeyron relation (Eq.2), the volume fraction of the fuel vapor above the surface is a function of the liquid boiling temperature;

  $$X_f = \exp\left[\left(-\frac{h_v W_f}{R}\left(\frac{1}{T_s} - \frac{1}{T_b}\right)\right)\right] \quad (2)$$

  where h_v is the heat of vaporization, T_s is the pool surface temperature, W_f and T_b are respectively the molecular weight and the boiling temperature of the fuel.

- considering a single step and instantaneous gas reaction between kerosene vapours and oxygen (Eq.3) ; the mixture fraction model is used to compute the heat release rate and the combustion products such as water, carbon dioxide and other species

  $$C_{14}H_{30} + \nu_{O_2}O_2 \rightarrow \nu_{CO_2}CO_2 + \nu_{H_2O}H_2O + \nu_{C0}C0 + \nu_S S \quad (3)$$

  where $\nu_i(i = CO_2, O_2, H_2O, CO, Soot)$ is respectively the stoichiometric coefficient of $CO_2, O_2, H_2O, CO, Soot$.

Energy transport consists of convection, conduction and radiation. Convection of heat is accomplished via the solution of the basic conservation equations. Gains and losses of heat via conduction and radiation are represented by the divergence of the heat flux vector in the energy equation.

The radiative source term is directly computed:

- outside flame zone : $\kappa I_b = \kappa\sigma T^4 / \pi$
- inside flame zone :. $\kappa I_b = \max\left(\chi_r \dot{q}''' / 4\pi ; \kappa\sigma T^4 / \pi\right)$

K is the total absorption coefficient of the source, $\dot{q}'''$ is the chemical heat release rate per unit volume and χ_r is an empirical estimate of the local fraction of that energy emitted as thermal radiation.

Both radiative and convective heat fluxes to the munitions surface are also computed. Net radiative heat flux is directly a function of the munitions surface emissivity (Eq.4) while convective heat flux strongly depends on the convection coefficient that is in LES calculations a combination of natural and forced convection correlations (Eq.5).

$$\begin{aligned} q'''_{net} &= q'''_{radt} + q'''_{conv} \\ &= \left[\varepsilon_s \int_{\left|\vec{\mathrm{s}}.\vec{\mathrm{n}}_\mathrm{w}\right|<0} \mathrm{I_s}(\vec{\mathrm{s}}) \left|\vec{\mathrm{s}}.\vec{\mathrm{n}}_\mathrm{s}\right| \mathrm{d}\Omega - \varepsilon_s \sigma T_s{}^4 \right] + h\left(T_g - T_s\right) \end{aligned} \quad (4)$$

Where ε_s and T_s are respectively the radiative emissivity and the temperature of the munitions surface. I_s is the radiative intensity from the flames to the munitions. T_g is the gas temperature and h is the convective coefficient that is defined as:

$$h = \max\left(C\Delta T^{1/3} ; \frac{\lambda_g}{L} 0.037 \,\mathrm{Re}^{4/5} \,\mathrm{Pr}^{1/3} \right) \quad (5)$$

ΔT is the difference between the wall and the gas temperature, C is the coefficient for natural convection (1,52 for a horizontal surface and 1,31 for a vertical surface), L is a characteristic length related to the size of the physical obstruction, λ_g is the thermal conductivity of the gas, and the Reynolds Re and Prandtl Pr numbers are based on the gas flowing past the obstruction.

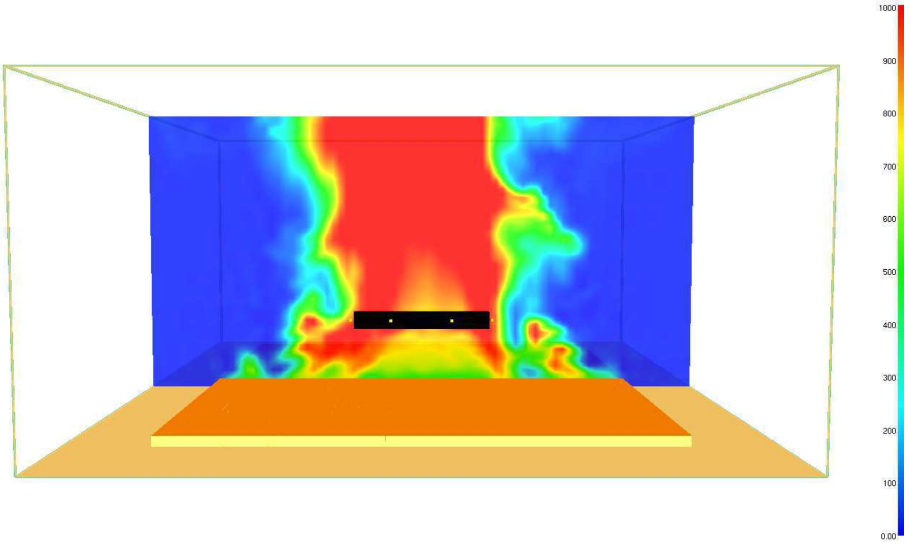
The standard Fast Cook Off test is simulated by modelling the kerosene pool fire (Fig.2a). Mesh size is uniform in the XYZ directions, mesh number is in the order of 650000 and the computing domain is 10 m x 10 m x 4 m respectively in the X, Y and Z directions. By a fast running CFD computation (less than 24 hours with an Intel 3.07 GHz frequency processor) it is possible to calculate both the 3D non-steady gas temperature and heat transfer between flames and munitions.

Second, the German-type test facility is also simulated by accounting for the injection and the combustion of liquid propane droplets all around the munitions (Fig.2b). The propane flow rate is set to 30 L/min and the axial distance between the munitions and the nozzles is assumed to be 2,5 meters. Mesh size is non uniform in the XYZ directions, mesh number is in the order of 300000 and the computing domain is 8 m x 5 m x 3 m respectively in the X, Y and Z directions.

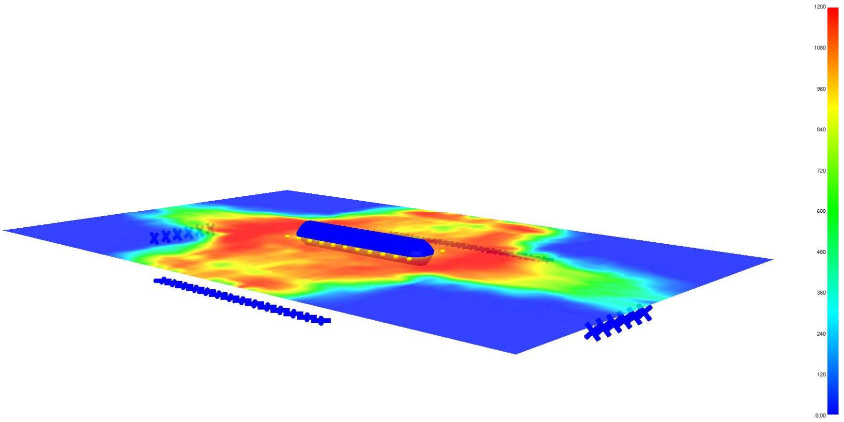
Finally, the US-type test facility is also simulated by modelling the injection and the combustion of propane below the munitions (Fig.2c). Mesh size is non uniform in the XYZ directions, mesh number is in the order of 250000 and the computing domain is 5 m x 5 m x 5 m respectively in the X, Y and Z directions.

Notice that the same steel-made and 2 meters long munitions is engulfed in the three computed fires. It is perfectly centered into the setups and no wind is assumed.

(a) Standard Liquid Fuel Fire Simulation



(b) German-type Alternative FireSimulation



(c) US-type Alternative FireSimulation

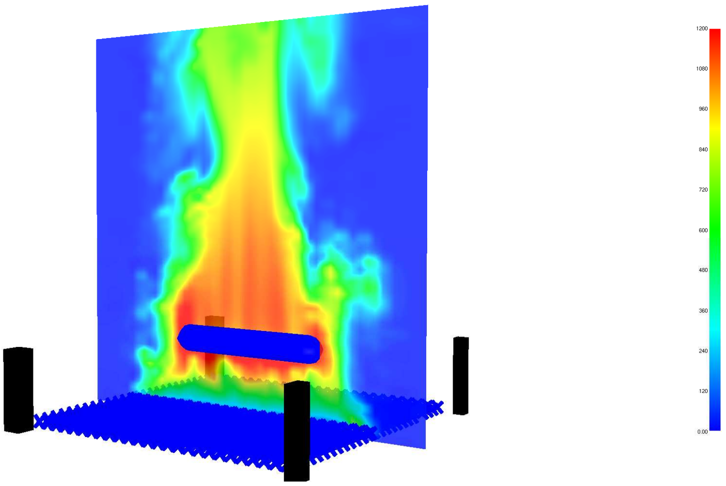


Figure 2 : Simulation of standard and alternative fires with engulfed munitions

RESULTS AND DISCUSSION

The aim of the numerical study is first to compare the thermal loads we can expect by using the standard liquid kerosene pool and the alternative test facilities. Then the effect of the munitions emissivity and the experimental parameters (such as propane flow rate or distance between nozzles and munitions) has been studied.

Comparison of thermal loads and soot production

As showed experimentally by Yagla et al. [7] the average temperature around the munitions can reach more than 800℃ when the gas fire test facilities are used (Tab.1). According to the numerical results it can locally achieve more than 1000℃ (Tab.1). The calculated thermal loads produced by the alternative setups are globally in the same order than one obtained within the liquid kerosene fire. As the tested munitions is 2 meters long, the head and aft-end of the item are not always engulfed in the flames what makes the computed temperatures decrease to values lower than 800℃. Concerning the average incident heat flux applied to the munitions it still remains in the same order than the standard one. The averaged values are around 100-120 kW/m² and are not spatially uniform as the standard one.

However two points are underlined by the computations and are discussed further. First the soot production is drastically decreased when the gas fire setups are used. Second, the calculated thermal load around the munitions strongly depends on the parameters which are linked to the test facility and easily abjustable as detailed in the next paragraphs.

Time-Averaged Values		**Standard Liquid Kerosene Fire**	**German-type Alternative Fire**	**US-type Alternative Fire**
Flame Temperature (℃)	T_{right1}	831	915	882
	T_{right2}	843	881	913
	T_{left1}	822	887	904
	T_{left2}	844	877	872
	T_{head}	947	817	650
	T_{aft}	937	823	749
Incident Heat Flux (kW/m²)	$\Phi_{incident}$	128	104	115
Soot Production	Integral of Soot Volume Fraction	3.77 e-6	8.49 e-7	5,9 e-7

Table 1 : Computed thermal loads and soot volume fraction produced by the standard and the alternative fire test facilities

Effect of the munitions emissivity

Concerning the pretty less sooty gas fires we may wonder if the assumption that sets the munitions emissivity to 0,9-0,95 (or very close to one) is still correct. In these cases deposit of soot particles on the munitions surface may not be as fast as within the kerosene pool fire and the emissivity of the tested item may not tend to one.

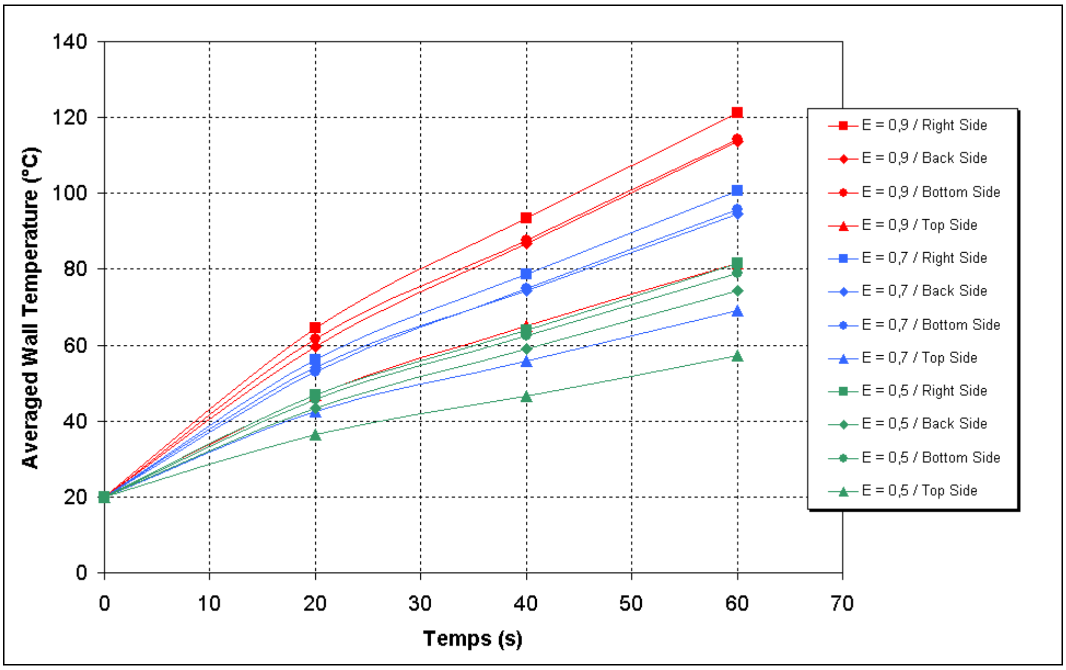


Figure 3 : Effect of the munitions emissivity on the calculated external tempeature

That is why this part is focused on the effect of the munitions emissivity $\varepsilon_{munitions}$ on this own heating. The thermal load produced by the German-type alternative fire is applied to the munitions that is steel-made. When $\varepsilon_{munitions}$ is varying from 0,9 to 0,5 the external temperature of the munitions at t = 60s is decreasing from 120°C to 80°C (Fig.3). That means the tested item is pretty much heated when its radiative emissivity is close to one. More energy is absorbed and the external temperature (and so on the internal temperature) rises up faster. Finally when $\varepsilon_{munitions}$ is close to one, i.e when the munitions is rapidly covered by soot particles, we could expect a shorter time to reaction of the munitions. Notice that the effect of soot deposit may be significant only if the initial emissivity of the munitions is low (0,5 or less).

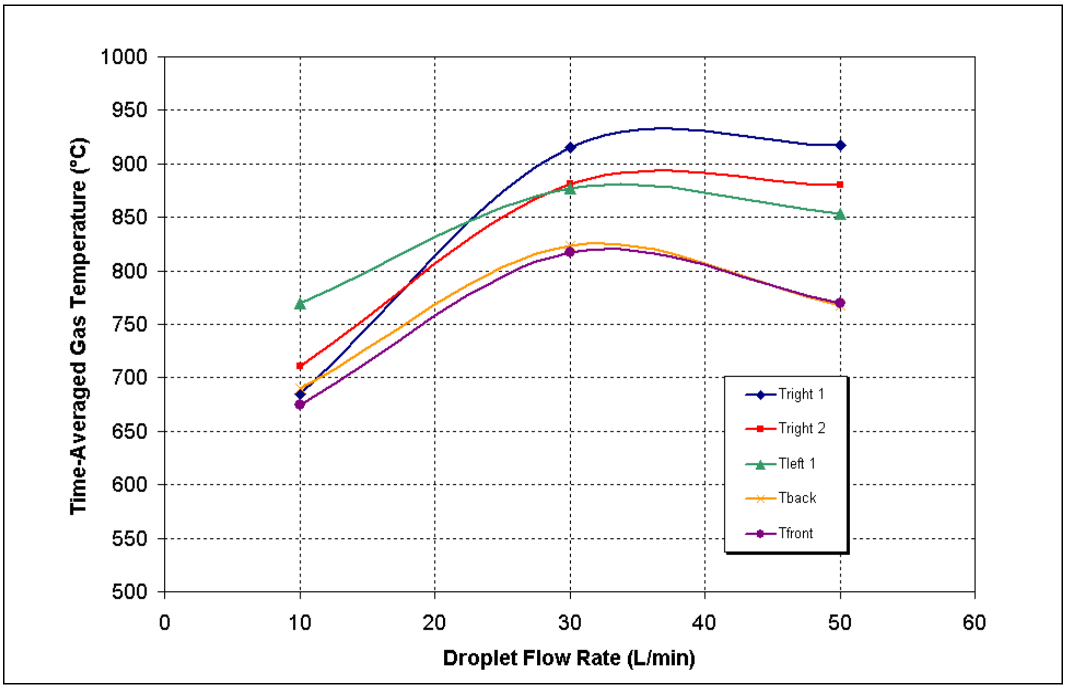


Figure 4 : Effect of the propane droplet flow rate on the computed flame temperatures around the munitions

Effect of the test setup parameters

The main difference between liquid kerosene pool and gas nozzles is the ability of the lattest ones to be adusted to produce the required thermal load. If the alternative test facility is not well calibrated the temperature and heat flux applied to the tested munitions can be strongly affected. For instance when the propane droplet flow rate is varying from 10 L/min to 50 L/min within the German-type setup average gas temperature around the munitions is not constant (Fig.4). An optimal value close to 30 L/min seems to be underlined. Thus some experimental adjustements may be needed to obtain satisfying results.

In the same way the distance from the nozzles to the tested item shall be well adapted to the munitions dimensions. At a given flow rate, gas temperature could not reach the required temperature level, if the distance is too large. For instance, by simulating the German-type setup and setting the droplet flow rate to 30 L/min, gas temperature does not reach 800℃ at the head end of the munitions.

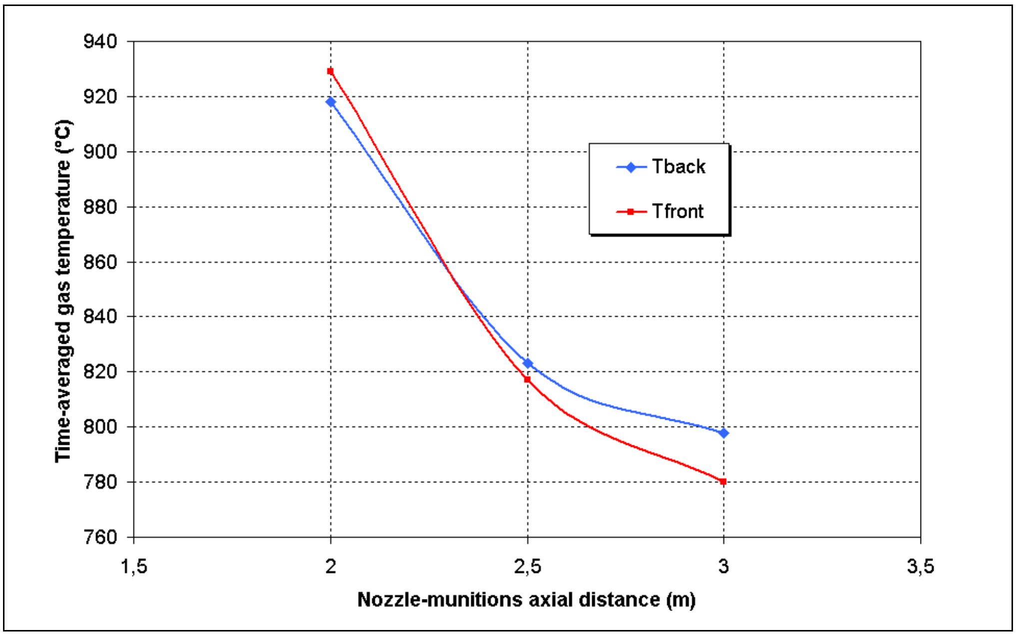


Figure 5 : Effect of the axial distance between the munitions and the nozzles on the flame temperatures at the head-end and aft-end of the munitions

CONCLUSION

For more than five years a significant work has been done by all nations to demonstrate the ability of the alternative fuel fires to mimic the standard liquid kerosene one. Three main sorts of setup have been experimentally evaluated : the German – type that horizontally sprays propane droplets around the munitions; the US-type that vertically injects gas propane below the munitions and the Swedish/Dutch-type based on premix fuel/air injection by orientable nozzles. The two first facilities have been numerically assessed In the present study.

As showed experimentally the computed thermal loads (gas temperature and incident heat flux) around the munitions are in the same order than the standard one. However the soot volume fraction produced by the alternative fires are pretty lower and the emissivity of unpainted munitions may be no more close to one as soon as the fire is ignited. That directly impacts the munitions heating and the time to reaction may be significantly modified.

Then some key parameters of the German-type setup have been moved to show their effect on the thermal load around the munitions. Unlike the standard liquid fuel pool the three types of alternative fire test facility must be adjusted to obtain satisfying thermal load. As shown by the present study optimal values of fuel flow rate and nozzle-munitions distance must be determined to engulf the whole tested item.

Such a study has confirmed the needs to calibrate the alternative fire test facilities in accordance with the tested munitions. Whatever the adjustments the alternative test facilities shall be compliant with the future AOP 4240 requirements in terms of thermal load around the munitions.

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