Heat transfer effects in the close proximity of a short duration pyrotechnic event

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Keywords: Pyrotechnic, reacting flows, temperature distribution, heat transfer

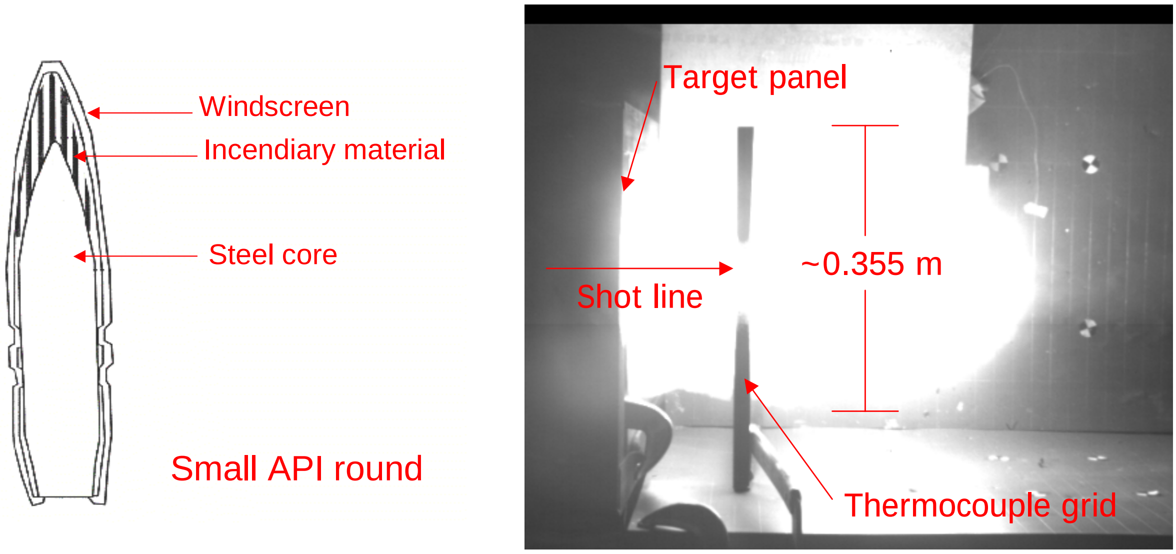
Abstract

Aircraft survivability in the event of a fire or, more importantly, a short duration pyrotechnic event can be better assessed if a thorough understanding of the heat and mass transfer of the event is known. However, it is becoming progressively more concerning that our present knowledge is far from complete when it comes to determining the local temperature field in such a pyrotechnic event. The ability to determine the temperature field associated with such a situation has implications for the survivability of the aircraft. These implications involve sensors that are capable of detecting such events that deploy quenching agents into the compartment/area of reaction. Experiments are being undertaken to develop an experimental simulation methodology to provide further understanding of this type of event from both the geometric and thermal state of a generated incendiary cloud. The simulator has already provided us with an understanding of the temperature field within the incendiary cloud. Preliminary studies have shown that the size and radiation emitted does not necessarily dictate the height at which the simulated event has to be in order to ignite a fuel pool. In addition, a complementary computational fluid dynamic study is being initiated in order to assist in the explanation of the competing energy transport mechanisms.

Introduction

Cabin fire and safety protocols on commercial aircraft rely heavily on our knowledge of fire dynamics, temperature distributions and thermal mass transfer of specific chemical components. If a fire has occurred because of a short duration pyrotechnic event then the scenario is further complicated, and is even more so if the event is in close proximity to a pool of fuel. In the military arena, the knowledge of such temperature distributions is far from complete. The measurements of the high temperatures afforded by near instantaneous combustion are fraught with difficulties and misunderstandings. For example, the high temperatures reached within the fireball of a small but highly volatile explosion or pyrotechnic thermal mass has not been measured with certainty and questions have recently arisen regarding the accuracy of such measurements. Indeed, the ignition of fuel by an incendiary device, such as an armour-piercing incendiary (API) projectile, has not been exhaustively covered. It is widely accepted that the energy is released uniformly and produces a homogeneous high temperature field. This temperature field is usually considered to be similar in size to that of the emitted spectral energy in the visible wavelength range.

As an example, consider the trajectory of a small arms API passing through a 6.35 mm thick (target) panel, figure 1. The API is composed of an inner steel core surrounded by an incendiary material and enclosed by a thin walled outer jacket, often referred to as the windscreen, figure 1(a). Once fired, the projectile impacts against the panel and the windscreen is effectively 'peeled' back as the API round is passing through the target. On doing so, the friction experienced by the incendiary material is sufficient to cause ignition, figure 1 (b). This figure shows that the trajectory of this API (from left to right) produces a large area of visible spectral energy, some 355 mm in diameter. The cloud did not provide a uniform temperature distribution throughout, *Dusina (2004)*. In addition, the duration of this type of event varies between 10 and 25 ms.



(a) **(b)**

Figure 1. Illustrative representation of an API and trajectory through target panel

The ability to measure the temperature of a dynamic radiant field is far from trivial. A number of methods have been used in the past to accomplish this. Of these methods, the most notable used are optical pyrometers whereby the brightness of a flame has been compared to the brightness of an incandescent filament in order to determine the flame temperature, *Shidlovskiy (1997)*. Other types of pyrometers have also been used, but have not been successful, for example, cinephoto pyrometer, photoelectric photometer and a color photometer, *Shidlovskiy (1997*). In comparison, temperature measurements of complex combustion within non-uniform temperature zones have been used successfully using a line-reversal methodology. This method may provide intermediate temperature distributions within the various zones of a flame; it is dependent upon the emission of characteristic spectral lines from the flame as viewed by a spectroscope, *Strong et al (1949)*.

However, even in the latter method, the temperature measurements only accounted for the average temperature across a flame region and the variations within the inner zones were unaccounted. Likewise, temperature fields with relation to flame height have been measured using a cinephoto pyrometer, *Shidlovskiy (1997).* Detailed temperature distributions were unattainable since this method could not provide measurements at intervals under 10 mm.

The aim of the present research is to develop a simulator that is capable of reproducing the thermal field within the structure of a functioning API event and to examine the extent of the fireball that evolves it was therefore, considered necessary to adopt a more simplistic approach, using high-speed thermocouples. Such temperature measurements have been performed earlier at a single fixed position in a closed system on different pyrotechnic materials, notably $Sb/KMnO_4$, *Beck (1989)*, and Pd/Al mixtures *Birnbaum (1978)*. Temperature profiles have also been measured using W-Re thermocouples for temperatures above 2000 deg C in $Mo/KClO_4$ material, *Gongpei et al (1994)*, and $W/KClO_4/BaCrO_4$ material, *Lao et al (1988)*, but again only at a fixed position in the system. Although bare bead W-Re type thermocouples are capable of measuring temperatures in excess of 2000 deg C they are very prone to oxidation that can lead to large errors occurring due to the reaction of the Tungsten (W) with Oxygen and therefore have to be used within inert environments to prevent the Tungsten from burning out. Given these complications, it was decided to measure the temperature using R and K type thermocouples that have maximum temperature of 1450 and 1250 respectively.

In addition to the temperature measurements it was considered expedient to utilize digital video analysis of the pyrotechnic event in order to observe the area of the spectral radiation. This methodology was further enhanced with the use of optical filters to suppress a significant portion of the visible wavelength region thereby allowing the hotter zones of the event, in the near infrared region, to be captured.

The temperature measurement methodology assists in the determination of the temperature quantitatively within an event, while the video analysis supports it qualitatively by differentiating between the fireball and the photon flash. Furthermore, a computational fluid dynamic (CFD) model is being developed to assist in the validation of the temperature levels and transfer mechanisms, and the preliminary results of this task are discussed.

Experimental procedures

The development of this pyrotechnic simulator enables use of a number of different methodologies for both quantitative and qualitative analysis of the transient events of an actual API event, coupled with the use of CFD to assist in the later validation of more complicated scenarios such as fuel ignition. The pyrotechnic charges were manufactured within the laboratory using, in the first case, a commercially available product (CPM) and in the second case, a chemical compound (LabMix) that was similar to that found within an API, Table 1. Here it may be observed that the CPM mixture does not contain the Magnesium element that both the API and LabMix has, but has 25% more Barium Nitrate in its formulation. The consequence of these differences is that the LabMix has a heat release similar to that of the API, being 3.11 Kcal/gm, as calculated from its expected reaction, whereas the CPM mixture can only provide approximately 50% of this heat release, i.e. 1.6 Kcal/gm. This similarity of the LabMix to an API was considered sufficient enough to validate a methodology for API incendiary research.

Chemical	Formulae	API	CPM *(Commercial)*	LabMix *(Experimental)*
Barium Nitrate	$Ba(NO_3)_2$	*50%*	*74.38%*	*50%*
Aluminum	Al	*24%*	*25.62%*	*24%*
Magnesium	Mg	*24%*	-	*24%*
Binder (Dextrin)	$(C_6H_{10}O_5)_n$	*2%*	-	*2%*
Heat Release	(Kcal/gm)	*3.13*	*1.6*	*3.11*

Table 1. Main chemical constituents & heat releases of the two mixtures

In both laboratory mixture cases, the compounds were formed into small cylindrical charges and could be horizontally mounted on the flame wall, shown in figure 2. This rig allowed the charge to be 'ignited' and to have thermocouples mounted such that they could be positioned, with an accuracy of 1 micron, at any position in the axial and radial direction from the surface of the burning charge, figure 3.

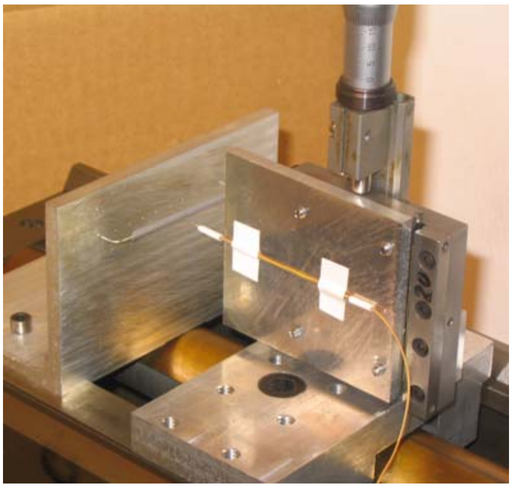


Figure 2. Experimental test rig

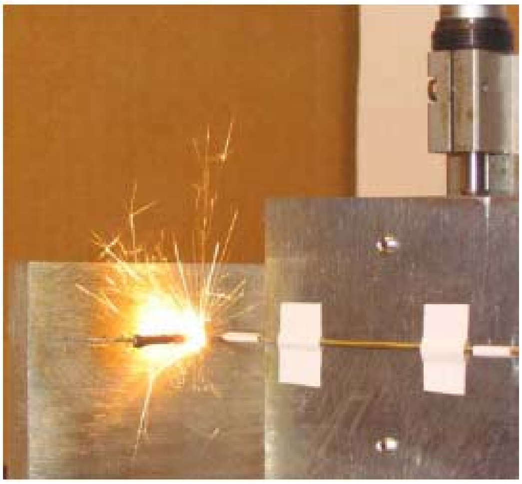


Figure 3. Thermocouple attached to rig

Further improvements to the charge were brought about by designing it with its own electronic 'match' such that it could be ignited in a more controlled manner. The testing components consisted of a main charge, an ignition initiator, heating element and support rod as shown in figure 4. Note there was a small change in the chemical constituents as shown in table 2. The initial dry mixture was prepared such that it could pass through a sieve with a mesh size of <200, that is equivalent to a particle size of approximately 74 μm.

The charge was located in a manner as before, however, an electrical connection was used as the charge initiator. The heating element was coiled around the support rod and embedded in the region of the initiating mix. It consisted of a 50.8mm (2 inch) long, 0.16mm diameter (34 gauge) Nichrome wire with a resistance of 2.73 Ohm. Difficulties had to be overcome in attaching and insulating this wire from the steel support rod. Once this was achieved, the charge could be ignited by attaching the heating element to wires capable of supporting 5 Volts and 1.5 Amps.

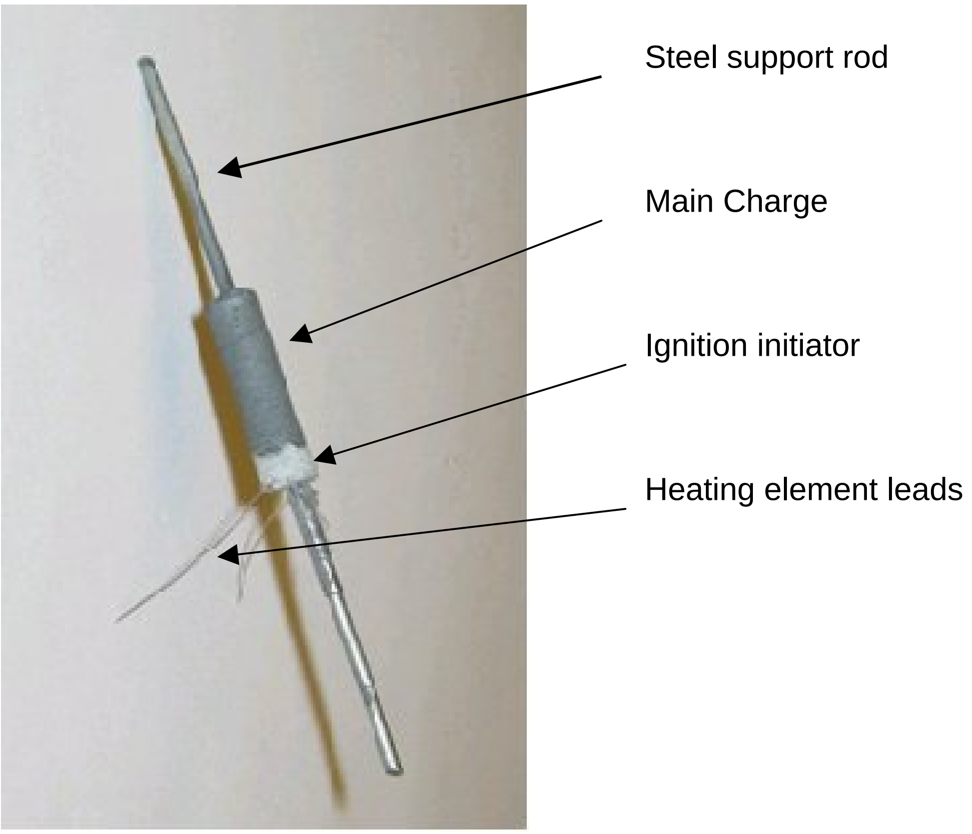


Figure 4. Components of the pyrotechnic charge

Charge	Chemical	Formulae	Quantity (by wt)	Mesh size
Main Charge	Barium Nitrate	$Ba(NO_3)_2$	50%	<200
	Magnalium	Mg-Al	48%	200
	Binder (Dextrin)	$(C_6H_{10}O_5)_n$	2%	<200
Initiator	Potassium chlorate	$KClO_3$	55%	<200
	Lead thiocyanate	$Pb(SCN)_2$	44%	<200
	Binder (Dextrin)	$(C_6H_{10}O_5)_n$	1%	<200

Table 2. Chemical constituents of the new LabMix main charge and its Initiator

Two different thermocouples were used in this study. A R-type and K-type with wire diameters of 36 and 40 AWG respectively, and different bead diameters. The thermal responses of these types are shown for comparison in figure 5. Although they both have similar response times the K-type would be used for these initial studies due to the vulnerability of the R-type to Oxidation and mechanical vibrations.

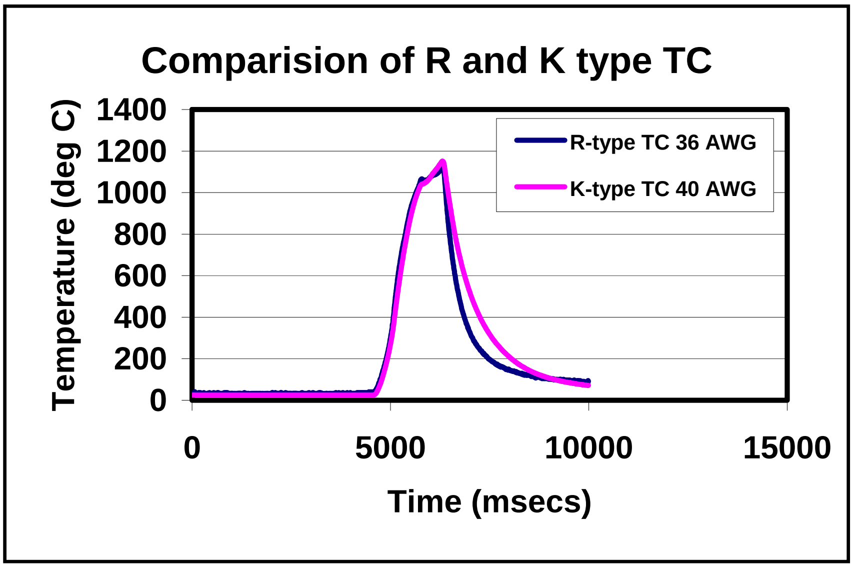


Figure 5. Thermal response of the R and K-type thermocouples

In order to provide further information on the extent of the spectral region in a pyrotechnic event, image analysis was utilized with the aid of specific spectral filters. In this case a spectral filter with a known wavelength, similar to that of the incandescence of the charge was used. Figure 6 shows the sharp cut-off filter in the spectral range of 580 – 610 nm.

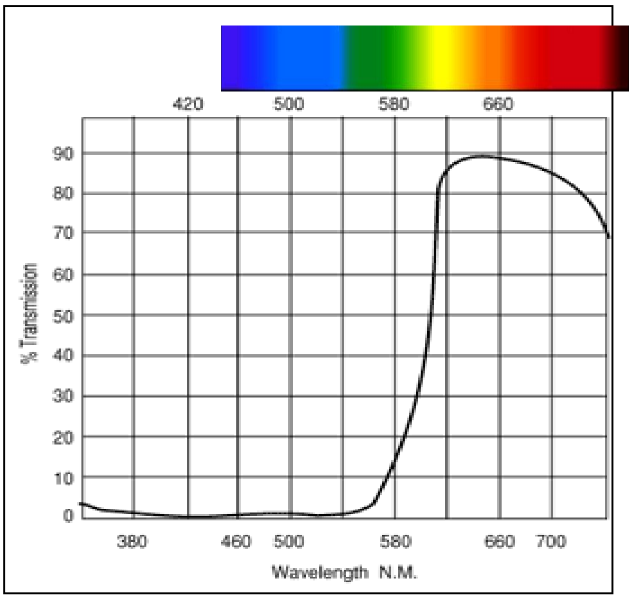


Figure 6. Spectral energy of the cut-off filter

To assess the ability of this filter to provide a clear definition of the ignition process from a CPM charge, it was necessary to establish how the filter would reduce the flame area of an event. This was achieved by simply imaging a naked candle flame with and without the filter present. The results together with the temperature distribution of approximately 1200^{0}C across the candle flame, are shown in figures 7 and 8.

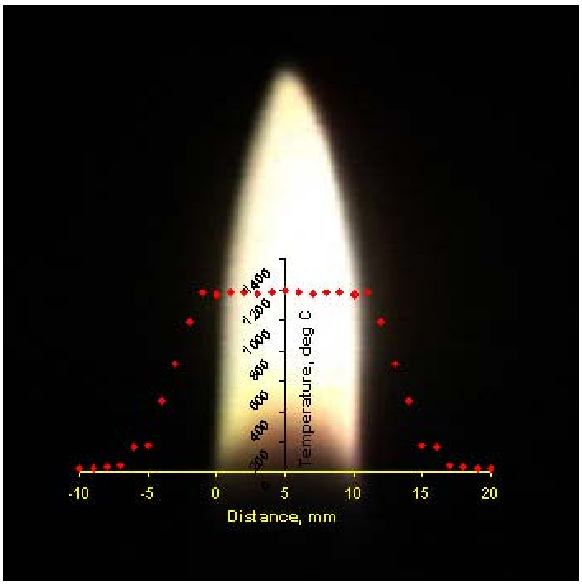


Figure 7. Naked candle flame

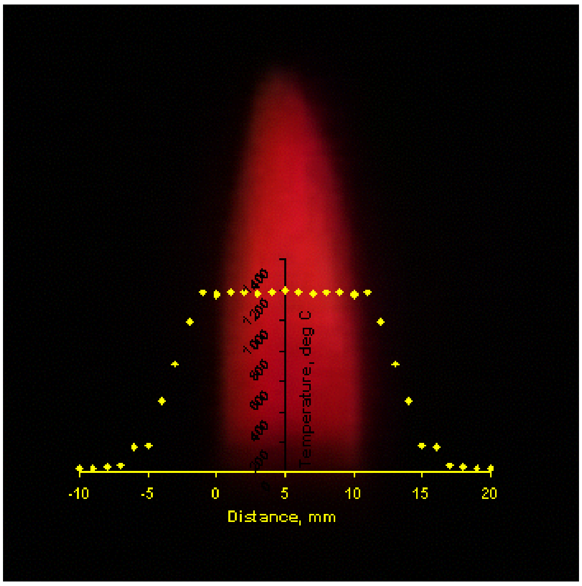


Figure 8. Filtered view of candle flame

This experiment demonstrated the ability of this filter to record the extent of the flame in both the radial and axial directions within acceptable limits. With the filter present, a reduction in width was 12% and in height, was 7%. The flame is three-dimensional and the outer edges of the flame will be considerably weaker than the internal structure of the flame.

Experimental Results

Temperature Distributions and Image Analysis

For the temperature study, test charges were made of both the CPM and the LabMix material. They were constructed 4 mm in diameter x 16 mm in length. These were mounted horizontally with 0.079mm diameter (40 gauge) bare bead K-type thermocouples arranged at specific locations on the side, top and bottom of the test charge. Due to the transient nature of the event only three temperatures could be obtained in any one particular run. The generated voltages were transmitted via an A/D converter into a PC computer at a sample frequency of 100 Hz for a total of 15 seconds. The local thermocouple temperature was then determined from a calibration using LabVIEW software.

The temperature distributions at the sides, top and bottom of the CPM charges were measured and the results are displayed in figure 9. This shows that there is little variation in the temperatures around the charges. The temperatures located within 2.0 mm of the surface could not be captured using K-type thermocouples for fear of destroying the thermocouple bead.

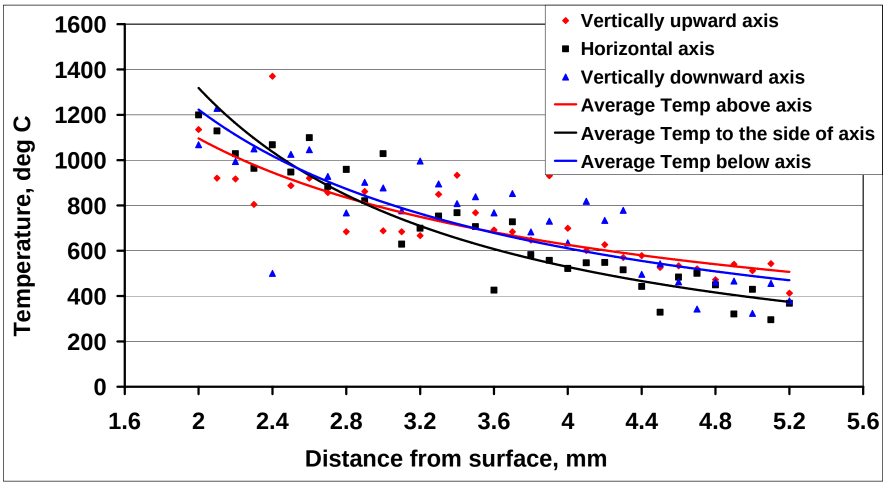


Figure 9. Temperature distributions around the 4 mm diameter CPM charge

For the case of the LabMix charges, the temperature distributions were completely different in as much that the temperature could not be measured within 20 mm of the charge surface for fear of melting the thermocouple, see figure 10. However, what was important was that the temperature distributions at the top and the bottom of the charge do appear to be different, with the temperature at the top being some 400^0 C greater in magnitude.

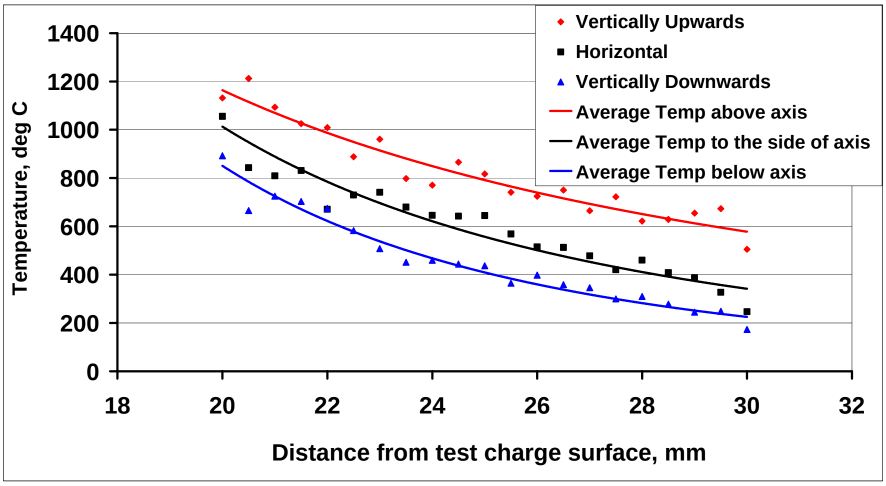


Figure 10. Temperature distributions around the 4 mm diameter LabMix charge

These results indicate the heat release from the LabMix formulation is twice that of the commercial product previously used (CPM). It also provides evidence that the rate of heat release does appear to have a significant effect on the temperature distribution, even when the two compounds have similar chemical proportions.

Image analysis of tests conducted on charges made from both CPM and LabMix using the filter as described above are shown in figures 11 and 12. In figure 11, the image is of the intense flash region of such an event using CPM and is of approximately 56 mm diameter, whereas figure 12 shows that the actual flame diameter, as observed through the specified filter, is no more than approximately 8 mm in extent.

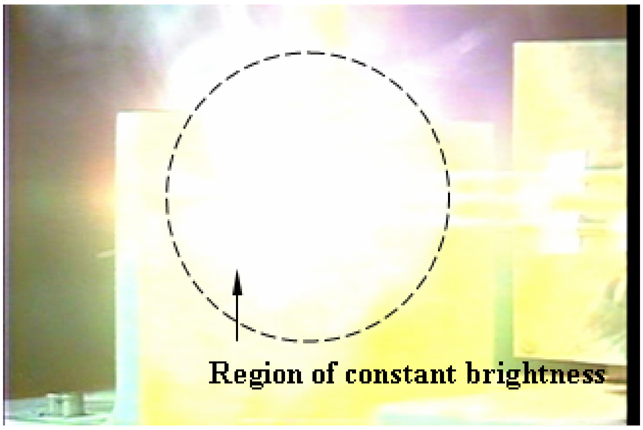


Figure 11. Intense flash from CPM charge

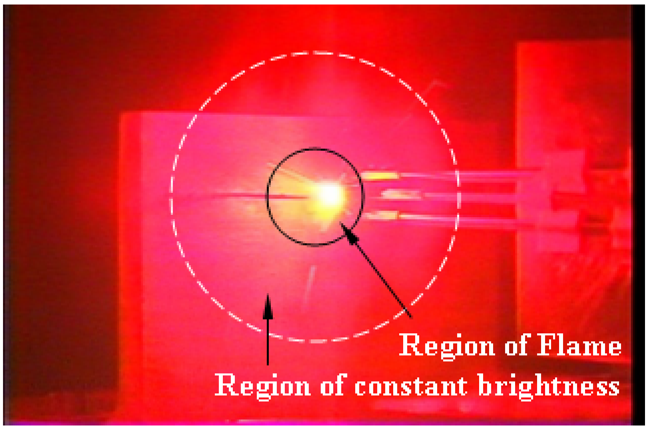


Figure 12. The region of flame may be observed using the spectral filter

This type of image analysis has provided a relationship between the fireball diameter to that of the flash diameter of the LabMix, figure 13. In this case, there appears to be, to 1st order approximation, a near linear relationship of flash to fireball ratio of about 7:1.

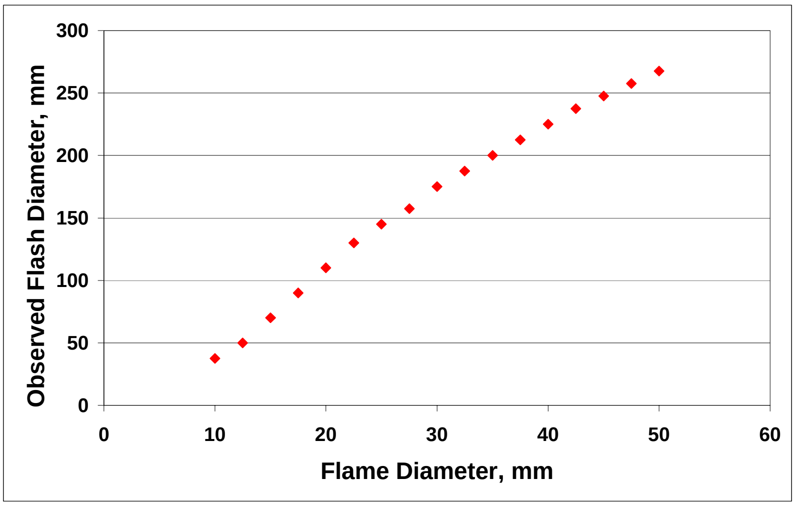


Figure 13. Relationship between flame to flash diameter for the LabMix, 4 mm diameter cylindrical charge

Initial Fuel Pool Ignition Studies

The ability of a pyrotechnic device to ignite and sustain a fire over a fuel pool is not well understood. This series of tests were devised to provide evidence that such a simulator may provide answers to a range of questions. Questions like,

- How does the height of charge above a fuel pool effect ignition and sustainment?
- How does the temperature of the fuel pool effect ignition and sustainment?

In order for this study to be undertaken a simple set-up was considered, with the charge being set at some height (H) above a small pool of Kerosene. The charge was positioned such that its axis was in the direction normal to the camera lens, see figure 14.

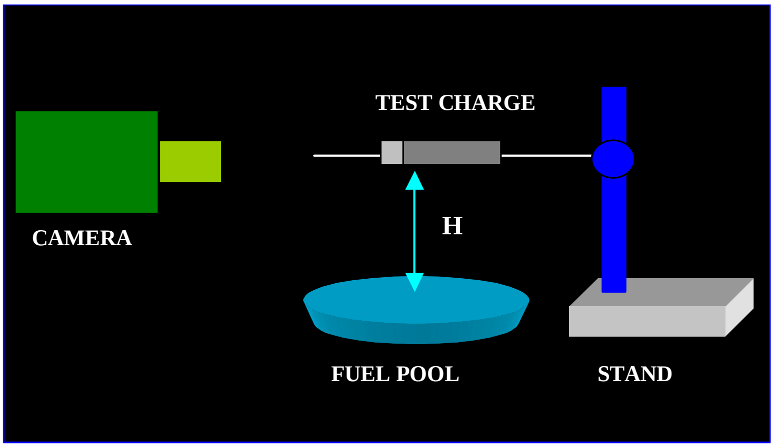
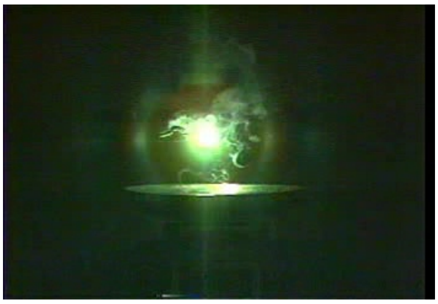


Figure 14. Diagram of experimental set-up to test fuel pool ignition

It was expected the response of providing a heat source over a fuel pool would increase its rate of evaporation without necessarily igniting the fuel. Based on this, the evaporation rate of the fuel for different temperatures was determined in the first instance. This was achieved by first measuring the weight of fuel in the container at a given fuel temperature and then recording its change over a time interval. Four fuel temperatures were chosen; 25^0 C, 50^0 C, 75^0 C and 100^0 C. All these were below the threshold of Kerosene's auto ignition temperature of 210^0 C. The results of these tests showed that the evaporation rate was approximately 0.026 gm/min, 0.045 gm/min, 0.17 gm/min, and 0.24 gm/min for each of the respective temperatures. However, it should be noted that temperatures of the Kerosene taken were approximate since the actual temperature was the heated flat plate upon which the fuel container was set. From this it can be expected that as the temperature of the fuel is increased, the evaporation (shown as the loss in weight of fuel from the container) is markedly increased. Its being hypothesized that ignition would occur at a higher height above the fuel surface for a given type of charge.

To test this hypothesis, a LabMix charge was ignited at a height of 90 mm above a fuel pool set at a temperature of 25^0 C, figure 15.

In this case, the charge appears to have completely engulfed the fuel and its container throughout the period. However, the actual fireball emanating from the charge was not close enough to provide sufficient heat for the pool to maintain a significant fuel evaporation rate sustaining a fuel burn scenario. Although the fuel vapor above the pool did ignite, this extinguished once the initial vapors had burned.


a) Ignition of charge


b) 0.2 sec


c) 0.56 sec

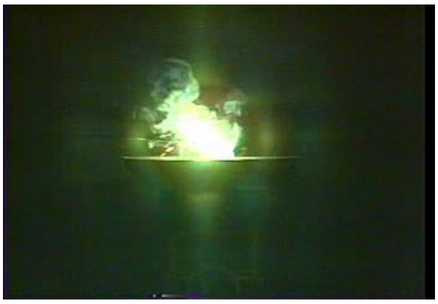

d) 0.8 sec


e) 1.05 sec


f) ignition is over short duration fuel burn

Figure 15. Ignition of an incendiary at a height of 90mm from the surface of fuel pool

A second set of images is shown in figure 16, where the charge has been placed at 50 mm from the fuel surface.


a) Ignition of charge


b) 0.25 sec


c) 0.48 sec


d) 0.95 sec


e) charge has ignited fuel vapor


f) 2.5 sec later, fuel is extinguishing

Figure 16. Ignition of an incendiary at a height of 50mm from the surface of fuel pool

Once again, the incendiary flash envelops the fuel and its container. However, this time the charge is able to transfer sufficient heat to ignite the fuel vapors at an earlier stage in its development. This has assisted temporarily in evaporating additional fuel from the surface to assist in the sustainment of the fire. Ultimately, the fire is not completely self-sustaining since insufficient fuel vapor is evaporated to prolong the burn. The fire eventually extinguishes itself without having used the complete fuel supply.

A series of tests have shown that this hypothesis is true. In the following figure 17, the height of a charge at which ignition occurs and is maintained, has to be lower for a low fuel temperature. This graph shows that for a given pyrotechnic charge, the height at which the fuel is ignited for a temperature of $25^0 – 50^0$ C is no more than 30 mm, whereas for a fuel temperature of 100^0 C, in which the evaporation rate is higher, the closest a charge can be is no less than 70 mm. It should be noted that in this last case the fire was self-sustaining and the entire amount of fuel was used.

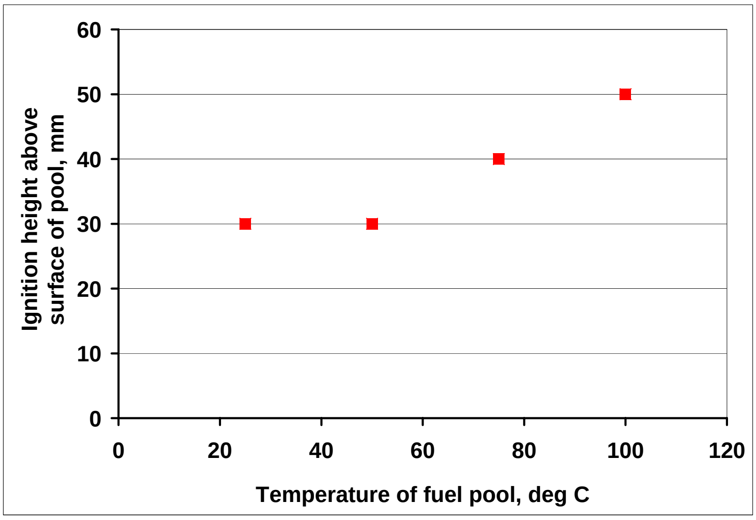


Figure 17. Variation of charge height to produce sustained ignition over a fuel pool

Computational Fluid Dynamic Study

In order to be able to explain some of the occurrences of short duration pyrotechnic events, it is anticipated that validated CFD models could be utilized to great efficiency. To this end some preliminary work is in hand to examine the variation in the temperature distributions around a cylindrical charge. However, it must be recognized that such short duration events are unlike those of the steady state condition. This is best illustrated by considering the temperature distributions around a constant temperature cylindrical surface as well as that of the instantaneous temperature distribution around a similar shaped body. Both computations were carried out using a commercial CFD package and the output is shown in figure 18.

In the case of the steady state distribution the temperature contours, depicting red as the hottest zone through orange, yellow, green, light blue to the coolest blue are shown as rising thermals. The largest temperature gradients are at the bottom of the cylinder and the lowest temperature gradients are at the top, as one might expect. However, for the case of the short duration event, the thermals do not have sufficient time to adjust and the temperature distribution is one of uniformity around the cylinder. The experimental evidence, as shown previously in figure 10, shows temperature differences between the upper and lower surfaces, and does not support the present CFD results. This is partly due to the laminar flow CFD model that has been considered, and further work is in progress to establish a turbulent flow model.

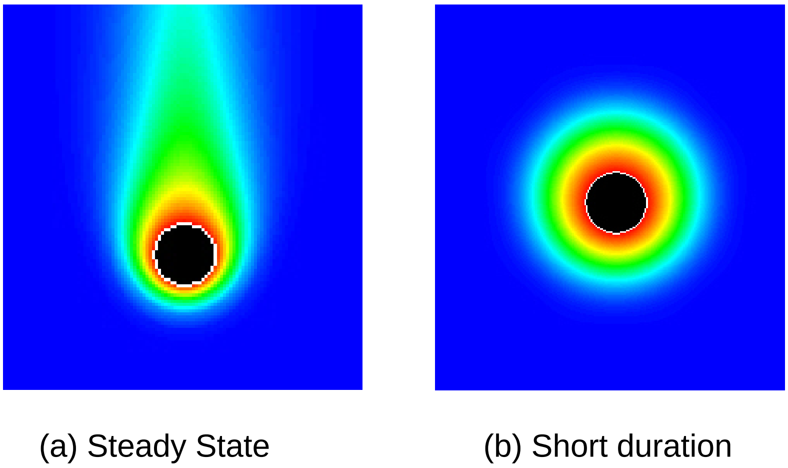


Figure 18. Comparison of the steady state and short duration temperature field around a cylindrical heated body.

Summary

This paper covers work being conducted in developing an API simulator utilizing non-ballistic pyrotechnic material and validating their effect with both thermometric means, image analysis, and CFD. In particular, this work has highlighted the following;

- Commercial products may be used in a limited capacity.
- Laboratory mixes can be made similar to that of API material.
- Thermocouple response times are sufficient to capture the event.
- The fireball diameter to photon flash diameter may be dependent on the charge size and composition.
- The high temperature associated with a charge is limited to the flame diameter and not the flash diameter.
- Initial temperature of a fuel pool is important to fire sustainment.
- Height of a charge above a fuel pool is important to fuel ignition and fire sustainment.

Further work is now being considered in order to establish correct procedures for specific, well defined tests, as well as testing of different fuels, improved instrumentation, external effects on the fuel (such as draughts, other gases being present), size and shape of charges.

Acknowledgements

The authors would like to thank the funding support from the Department of Defense, the Joint Aircraft Survivability (JAS) program office, John S Kemp of the USAF 46th Test Wing, Aerospace Survivability & Safety Flight, and the Department of Aerospace Engineering at the University of Cincinnati.

Notation

Al	=	Aluminum
$BaCrO_4$	=	Barium Chromate
$Ba(NO_3)_2$	=	Barium Nitrate
$KClO_4$	=	Potassium perchlorate
$KMnO_4$	=	Potassium permanganate
Mo	=	Molybdenum
Pd	=	Palladium
Re	=	Rhenium
Sb	=	Antimony
S	=	Sulfur
W	=	Tungsten

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