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VISUALIZING THE THERMAL EFFECT OF THERMOBARIC EXPLOSIVES

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Abstract: *Measuring the temperature of an explosion has always been a big challenge. In the last several decades many different techniques were used for this purpose, but none of them were reliable enough. Very fast temperature rise and fall time that occurs in explosions is very difficult to register with any kind of sensor. This paper presents a different approach that uses a high-speed infrared camera to record the explosion temperature. Optimal camera setup was achieved after a few attempts. The result was a detail infrared video of the explosion. Expansion of the products of detonation is clearly visible in this video. Different sets of data were extracted from the infrared recordings, like temperature-time and temperature-distance graphs. The results confirmed that the thermal effect of the thermobaric explosives can be reliably measured with this technique.*

Keywords: *temperature, explosive, thermovision, infrared camera.*

1. INTRODUCTION

Detonation is a process that usually lasts tens of microseconds. During this time, all of the explosive molecules turn to gaseous products of detonation. Then, these products expand (explode), and that expansion can last for hundreds of microseconds [1].

If the explosive composition [2] is thermobaric [3-5], i.e. it contains a metal fuel (like Al, Mg, B) and an oxidizer (like NH_4ClO_4), then there is a third process that occurs after the expansion of the products of detonation – aerobic combustion of the metal fuel, which can last for tens of milliseconds [2-5].

This post detonation aerobic combustion reaction gives thermobaric explosives (TBE) improved incendiary and blast effects, compared to conventional high explosives. Shock waves generated by their detonation have a much longer duration then those generated by conventional high explosives, and also have a greater lethal radius [6]. In a confined space, TBE can cause a series of reflected shock waves, which make them highly effective for the destruction of soft targets like tunnels, bunkers, underground structures, buildings, field fabrications, etc.

The longer the post detonation aerobic combustion lasts, and the higher its temperature is, the better are the destructive capabilities of the TBE.

Since this temperature changes rapidly and it lasts for a very short time, measuring it is a very difficult task. The most advanced probes available (thermocouples) are expensive, and cannot withstand the explosion if they are actually in it, so they have to be used only at a certain distance from the explosion [7]. Optical pyrometers, that can measure the temperature from a distance, can only measure surface temperatures at a certain point. They also have to go through a complicated calibration to measure the temperature of the explosion products like dust and different gas products.

For these reasons there are not many published papers that try to deal with this problem. With the advancements in infrared imaging techniques, most importantly the increase in infrared camera frame rates, a new approach to temperature measurements became possible.

This paper will describe the technique has been established in Military technical institute through several iterations of trial and error [8, 9]. Infrared recordings were used to obtain different sets of data like temperature–time and temperature-distance graphs. Also, some of the known characteristics of the products of detonation expansion were noticed, which helped to interpret the acquired images.

Extracting temperature–time graphs from infrared recordings of explosions was also done by researchers from China [10], but it was difficult to compare results of this research with theirs. For example, their infrared recordings show that the explosion lasts a lot longer than recordings presented in this work.

2. EXPERIMENTAL SAMPLES

The experiments that are presented in this paper were done on 50 mm diameter cylindrical cast thermobaric explosive charges. The charges were made with the following components:

- octogen (DINO − Norway), according to MIL-H-45444,
- aluminium, according to MIL-STD-129,
- magnesium (ECKA GRANULES − Austria), according to MIL-DTL-382D,
- ammonium perchlorate, 7-10 μm, obtained by grinding 200 μm-AP on a vertical hammer mill ACM-10,
- polymeric binder, based on hydroxyterminated polybutadiene (Tanyun, China) cured by isophorone-diisocyanate, including additives (plasticizer, antioxidant, and bonding agent) [11].

The % mass fraction of the components of the explosive were HMX/AP/Al/Mg/HTPB = 45/10/21/9/15. After the manufacturing process, the charges were removed from their molds, and cut to 400 g samples. The density was measured (MIL 286 B method, on the Mohr's scale in toluene at 25°C) to be 1.7 g/cm^3, and the detonation velocity was measured by electrocontact probes to be 7150 m/s.

3. EXPERIMENTAL SETUP

Recordings of the explosions were made with a high-speed infrared (IR) camera FLIR SC7200. The camera characteristics are given in Table 1. Software "Altair" was used for data acquisition and analysis.

Table 1. Characteristics of the FLIR SC7200 camera

Spectral range		1.5-5.1 μm
Maximum screen resolution		320 × 256 px
Camera sensitivity (NETD)		< 20 mK
Aperture		F/3
Pitch		30 μm
Technology		In-Sb
Objective		50 mm
Field of view angle of the objective		11° × 8.8°
Total calibrated temperature range		5 − 2500 °C
Calibrated temperature sub ranges	TR-1	5 − 300 °C
	TR-2	300 − 1500 °C
	TR-3	1500 − 2500 °C

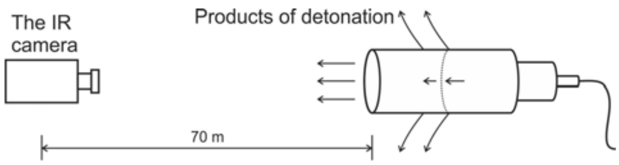
Parameters like camera frequency, distance between the camera and the explosive, and the field of view were different for every experiment presented here, and will be accentuated when needed. The camera frequency can only be increased if the field of view (and the resolution) is reduced.

The explosive was always placed 2 m from the ground and the axis of symmetry was aligned towards the camera. A photo of a sample is presented in Picture 1. Initiation of the samples was done on the far end of the charge, so that the direction of the detonation wave pointed directly to the camera (Picture 2).

Picture 1. Photo of a sample on a stand

The camera is calibrated to a black body, which means that the temperature has to be corrected by entering the emissivity of the recorded object in the software. Unfortunately, emissivity of an explosion fireball proved difficult even to estimate. The fireball is a mixture of solid and gas particles, some of them reacting with others, which changes the chemical composition of the system really fast. Also, there is no spatial homogeneity, so there are parts with higher or lower emissivity.

Because of this, the temperature that we measure is actually lower than the real temperature. But, even though we can't measure the absolute value of the temperature, we can compare different measurements because the emissivity is always the same for the same explosive composition. For the same reason, the results can't be compared with different techniques for measuring explosion temperature.



Picture 2. Experimental setup

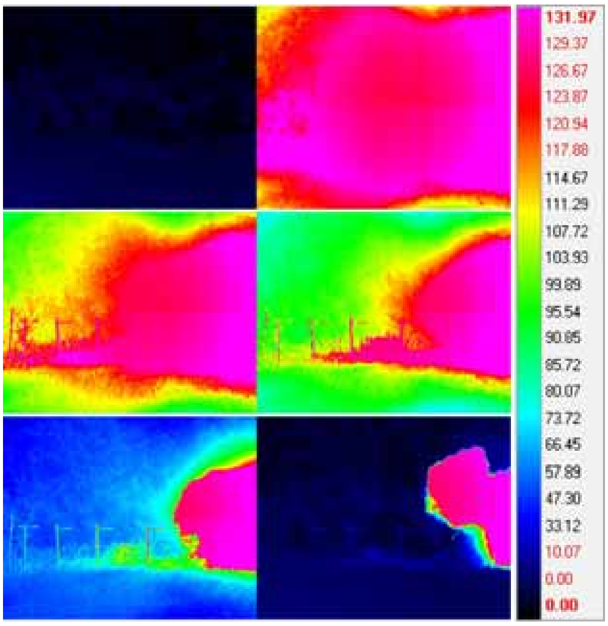
4. RESULTS AND DISCUSSION

Many high-speed infrared recordings were made before the optimal experimental setup was determined. Here, we present three recordings, each representing a step towards the optimal setup.

4.1. Infrared recordings

1) 174 Hz recording

The first recordings done with the FLIR camera were used to get some insight into the IR scene of the explosion process. The largest field of view was used, with the resolution of 320 × 256 px. The camera was placed 70 m from the explosive. Recording frequency was 174 Hz, which is 5.75 ms per frame, and the upper limit of the temperature range was set to 130°C. 6 frames are presented in Picture 3.



Picture 3. 174 Hz recording, full resolution 320 × 256 px, camera – explosive distance 70 m

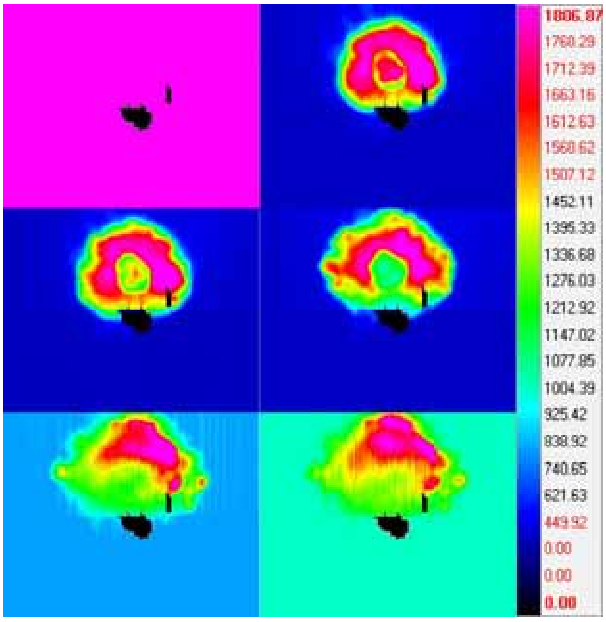
These frames show that the 174 Hz frame rate is too slow and that the temperature limit needs to be much higher. The first several frames mostly just show complete camera saturation, after which only the cooling of the air can be seen. There is no important information that can be extracted from these frames.

2) 655 Hz recording

After several recordings with different camera setups we realized that only the area 2 – 3 m around the center of the explosion is interesting to record. The field of view was narrowed down to 160 × 128 px, which allowed us to record the explosion at 655 Hz (Picture 4). This frequency is high enough that we can observe some interesting details about the explosion. During these experiments, the infrared camera had some dead pixels, but this didn't impact the results.

This experimental setup allows us to see two different areas of combustion: the outer, ring shaped area and the inner, circle shaped area. The ring shaped area does not complete a full circle - on the bottom side there is a drop in temperature. This occurs because the stand for the explosive, shown in Figure 1 slows down the downward expansion of the products of detonation. The inner, circle shaped area burns for less time than the outer area simply because it contains less fuel and oxidizer (Al, AP).

The two areas are not actually inside one another. They are both at a certain distance from the center of the detonation, and the circle shaped area is even a little farther than the ring area. The explosive charge is cylindrical which causes the products of detonation to initially spread in two distinct ways - lateral and frontal ejection. This behavior is sketched in Picture 2. Since the frontal ejection is aligned towards the cameras it is recorded as the inner, circle shaped area. The same way, the lateral ejection makes a torus shaped cloud of fuel and oxidizer which is recorded as the outer, ring area. The two areas are not differentiated too much - it is a pretty smooth transition between the two, but it is enough to be easily noticeable in the recordings.

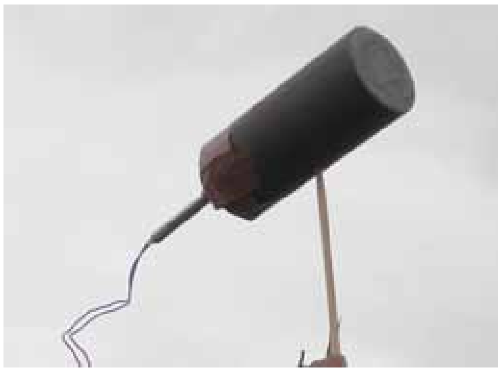


Picture 4. 655 Hz recording, resolution 160 × 128 px, camera – explosive distance 70 m

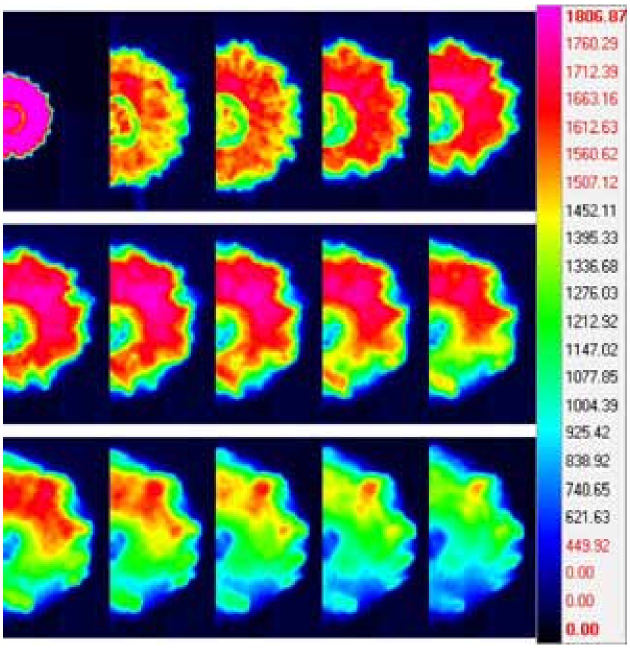
These frames show that the 655 Hz frame rate is fast enough to capture the aerobic combustion of the fuel, but not enough to capture the initial expansion of the fuel with the products of detonation.

3) 1459 Hz recording

In order to obtain a more detailed recording, the frequency was increased to 1459 Hz, but the size of the frame had to be reduced to 64× 120 px. With such a small frame, only one side of the explosion could be recorded, in this case the right side. Also, the camera – explosive distance was reduced to 50 m, which further increased the explosion details. The stand was replaced with a small wooden pole on which the explosive was impaled (Picture 5). Because of this the products of detonation could expand in all directions and the ring shaped area completed a full circle (Picture 6).



Picture 5. Photo of a sample on a pole

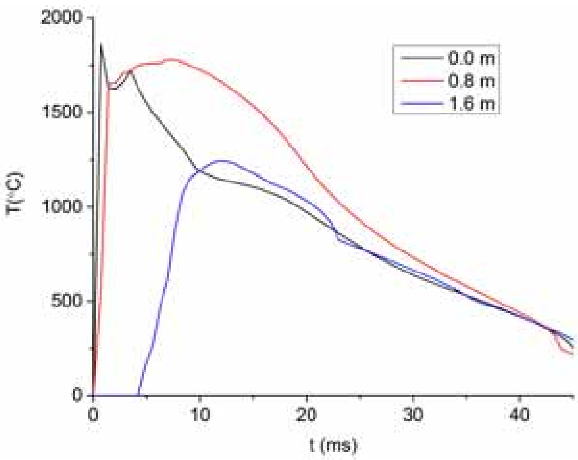


Picture 6. 1459 Hz recording, resolution 80 × 128 px, camera – explosive distance 50 m

In order to increase the frequency even more, the size of the frame would have to be reduced to 64× 8 px which is not enough to capture enough of the explosion. So the optimal setup for recording explosions of TBE with this camera is the one in Picture 6. This setup allows for the most precise measurements, while having a frame size that's big enough to fit at least half of the fire ball.

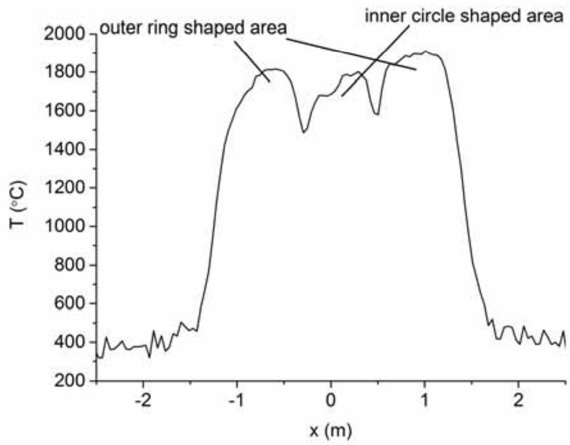
4.2. Extracted graphs

Every pixel on every frame can be considered as a temperature measurement in a single point in time. Taking the same pixel for multiple frames gives a temperature-time (T-t) graph in the same way an optical pyrometer or a thermocouple probe does. One T-t graph is presented in Picture 7. There are actually three T-t curves here: one that is from the center of the explosion, one at 0.8 m from the center and one at 1.6 m.

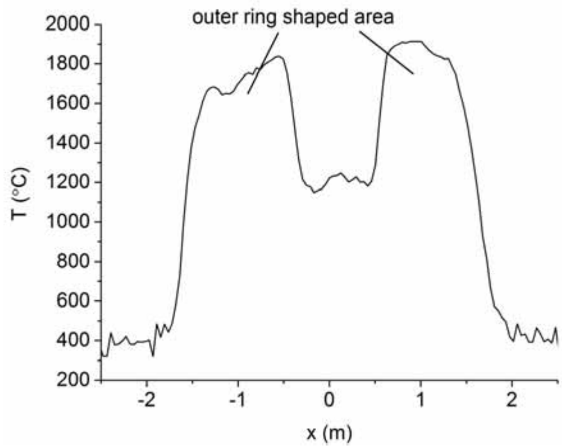


Picture 7. Temperature-time graph

On the other hand, considering only one frame, and taking all of the pixels in one horizontal line (that is going through the explosion center) gives a temperature-distance (T-x) graph that shows spatial temperature distribution. This can only be done with a high-speed infrared camera and no other technique. Picture 8 shows a distribution where both the inner and the outer area are present, and in Picture 9 only the outer area can be seen.



Picture 8. Temperature-distance graph with both the inner and the outer area



Picture 9. Temperature-distance graph with only the outer area

5. CONCLUSION

High-speed infrared camera is shown to be a powerful tool for visualizing the thermal effect of thermobaric explosives, but in the same way for the explosives in general. Also, temperature measurements can be made in different ways, and a lot of data can be extracted from the recordings. These measurements can be compared with each other but not with a measurement made by a different instrument, because the emissivity of the explosion cloud is unknown.

Figuring out this emissivity is a difficult task, but it would enable determining the absolute temperature from the recordings.

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