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INVERSE THERMOVISION ANALYSIS OF HIGH-ENERGY PHENOMENA

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Abstract: *Thermovision monitoring provides an effective non-contact approach for the analysis of rapid thermal processes by enabling high-speed recording of infrared radiation response and reconstruction of temperature–time evolution. This paper presents an inverse thermovision reconstruction approach for the characterization of transient high-energy explosive processes based on radiometric analysis of fireball emission and a physics-based measurement model. Experimental validation was performed using RDX-based PBX thermobaric explosive formulations, with fireball development in static conditions in open-field tests, recorded by a high-speed infrared thermovision system operating at 1466 Hz. The reconstructed temperature-time profiles were analyzed to extract characteristic parameters, including maximum temperature, time to peak temperature, cooling rate, and integral temperature index describing the cumulative thermal response. Since thermovision systems measure radiometric signals and not the direct thermodynamic temperature, the reconstruction procedure considers emissivity, spectral response, and atmospheric transmission effects. The results demonstrate that different PBX formulations exhibit distinct thermal signatures, enabling comparative characterization based on fireball evolution and cooling dynamics. The proposed methodology confirms the potential of high-speed thermovision techniques combined with inverse reconstruction methods for quantitative non-contact analysis of transient high-energy explosion phenomena.*

Keywords: *infrared thermovision; infrared radiometry; inverse temperature field reconstruction; radiometric model; high-energy explosive phenomena; fireball dynamics; PBX explosive formulations*

1. INTRODUCTION

Thermovision technique represents one of the most important non-contact methods for spatial and temporal analysis of temperature fields and rapid thermal processes. It is based on the detection of infrared radiation emitted by the observed object and the determination of temperature-related parameters using a radiometric model that incorporates radiation source characteristics, optical system properties, atmospheric transmission, and detector response [1].

Unlike contact temperature measurement methods, thermovision systems enable non-invasive monitoring of dynamic processes with high spatial and temporal resolution, which has resulted in their application in material characterization, non-destructive evaluation, energy systems, biomedical applications, and analysis of complex thermal phenomena [1]. The physical basis of thermovision measurement relies on thermal radiation, where radiation intensity and spectral distribution depend on temperature and emission characteristics of the observed surface. However, real measurement systems deviate from the ideal black-body model due to material emissivity, detector spectral response, optical transmission characteristics, and atmospheric attenuation effects [2, 3].

For rapid thermal processes, such as high-energy explosive phenomena, temperature cannot be directly measured but must be reconstructed from the recorded infrared radiation signal. This represents an inverse thermovision problem, where the temperature field is determined from an indirectly measured detector response. Reliable reconstruction requires physically based radiation transfer models, additional constraints, and appropriate regularization methods to obtain stable and physically consistent solutions [4,5].

High-speed thermovision systems are particularly relevant for the analysis of explosive processes. Unlike nuclear explosive phenomena, where energy release is associated with nuclear transformations and intense high-energy radiation, conventional and thermobaric explosives involve rapid thermochemical reactions, heating of

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detonation products, fireball formation, and subsequent energy transfer through visible and infrared radiation [6-8].

The temperature evolution of an explosive fireball depends on chemical composition, charge density, fuel-to-oxidizer ratio, explosive geometry, and experimental conditions. Measurements of high-energy HMX-based systems have demonstrated temperature levels of approximately 3600 K during early stages of detonation product development [9]. However, the measured infrared signal is not a direct temperature value but a radiometric response affected by emissivity, spectral characteristics of the measurement system, and atmospheric propagation conditions. Therefore, accurate temperature estimation requires appropriate correction procedures and inverse thermovision reconstruction methods [10].

Modern high-speed infrared thermovision systems enable monitoring of fireball evolution, including temperature rise, maximum response, and cooling phase. The resulting temperature–time profiles provide characteristic thermovision signatures that can be used for comparative analysis of different explosive formulations [6,8,11].

The aim of this paper is to develop an inverse thermovision reconstruction approach for the characterization of transient high-energy explosive processes using high-speed infrared recording. The analysis focuses on the determination of maximum reconstructed temperature, time to peak temperature, cooling rate, and integral thermal response as physically based parameters for comparative characterization of PBX explosive formulations.

2. THERMAL-RADIATIVE PHENOMENA

2.1. Energy Balance of High-Energy Processes

Transient high-energy processes are characterized by extremely rapid changes in the internal energy state of a system, during which initially deposited energy is transformed into different energy components, including thermal, mechanical, and radiative energy. In explosive processes, this transformation occurs within a very short time interval and involves heating of detonation products, shock wave formation, expansion of gaseous products, and emission of electromagnetic radiation.

The total energy balance of the system can be expressed as:

$$E_{chem}=E_{th}+E_{mech}+E_{rad}+E_{res}$$

where E_{th} represents the thermal energy accumulated in detonation products, E_{mech} represents mechanical work and shock wave energy, E_{rad} represents energy emitted in the form of electromagnetic radiation, and E_{res} represents the residual energy component not directly included in radiometric measurement.

During the initial stage of explosive development, the dominant process is the transformation of chemical energy into the internal energy of detonation products and mechanical work:

$$Echem \rightarrow Eth+Emech$$

After reaching the maximum temperature response of the system, energy transfer mechanisms toward the surrounding environment become dominant:

$$Eres=Erad+Econv+Eexp+Emix$$

where the components represent energy losses due to thermal radiation, convection, expansion of detonation products, and mixing of products with the surrounding environment.

Thermovision systems measure only the radiative component leaving the system and do not provide direct information about the total released energy of the process. The measured signal depends on temperature, emissivity, spectral characteristics of the source, optical system properties, measurement geometry, and atmospheric attenuation [1–3].

Therefore, temperature determination from the infrared signal represents an inverse problem:

$$SIR(t) \rightarrow T(t) \rightarrow Eth(t)$$

where the temperature dynamics of the system and characteristic parameters of energy evolution are reconstructed from the measured radiometric signal.

2.2. Characteristics of Explosive Phenomena

The fundamental difference between nuclear and chemical explosive processes originates from the mechanism of energy release (Table 1). In nuclear explosions, energy is released through transformations of atomic nuclei (fission or fusion), resulting in the formation of an intense radiation field within an extremely short time interval.

From the viewpoint of thermovision technique, this difference is of fundamental importance. In nuclear phenomena, infrared emission represents a later stage of system evolution, occurring after the dominant radiation shifts toward lower-energy spectral regions. In chemical explosive processes, the infrared signal more directly corresponds to the development of the fireball temperature field and the cooling dynamics of detonation products.

Table 1. Fundamental physical differences between nuclear and conventional explosive phenomena

Parameter	Nuclear explosion	Conventional/Thermobaric explosion
Energy source	Nuclear reaction (fission/fusion)	Хемијска реакција
Characteristic temperature	10^6–10^7 K in the early radiative phase	Approximately 3000−5000 K
Dominant energy transfer mechanism	Radiative transfer	Thermochemical, radiative, and mechanical processes
Early development phase	X and γ radiation	Visible and infrared emission
Dominant spectral range	X → UV → VIS → IR	VIS + IR
Shock wave development	After the initial radiative phase	Practically simultaneous with detonation
Possibility of thermovision characterization	Limited due to early radiative effects	Direct analysis of thermal response

2.3. Temperature Reconstruction

The evolution of a high-energy source can be described through several characteristic stages. During the initial phase of nuclear processes, high-energy X- and γ-radiation dominates, rendering conventional infrared systems inapplicable because of the spectral limitations of infrared detectors.

As the fireball expands, its temperature decreases and the spectral distribution of emitted radiation gradually shifts toward the visible and infrared regions. At this stage, high-speed optical and thermovision techniques can be employed to determine:

- radiation temperature, T(t);
- fireball expansion dynamics, R(t);
- radiative energy flux.

However, the reconstructed temperature corresponds to the radiation temperature rather than the direct thermodynamic temperature of the entire source volume.

The principal limitations of infrared measurement arise from:

- the limited spectral range of the detector;
- the temporal response of the measurement system;
- the variable emissivity of the source;
- atmospheric absorption and scattering;
- the inverse nature of the temperature reconstruction problem.

Consequently, thermovision systems do not measure temperature directly; instead, they record a radiometric signal that is transformed into an estimate of the temperature field through a physics-based radiative transfer model [1-5].

2.4. Explosive Processes Characterization

For conventional and thermobaric explosives, thermovision provides an effective non-contact technique for analyzing the temporal evolution of the fireball. The temperature of detonation products typically ranges from approximately 3000 to 5000 K, depending on the chemical composition of the explosive and the conditions of the explosion [10], [11].

In this study, the explosive process is characterized by the following parameters: T_{max}, t_{max}, dT/dt, E; where T_{max} is the maximum reconstructed fireball temperature, t_{max} is the time required to reach the maximum temperature response, dT/dt denotes the cooling rate, and E is the integral energy index representing a relative measure of the overall thermal response during the observation interval.

These parameters do not represent a direct measure of the chemical energy released by the explosive. Instead, they provide a physics-based framework for comparing different high-energy systems through inverse thermovision reconstruction.

3. THERMOVISION OF EXPLOSIONS

Unlike nuclear explosive phenomena, where the initial stage of energy release is dominated by intense X- and γ-radiation, conventional and thermobaric explosives release most of their energy through thermochemical reactions, heating of detonation products, fireball formation, and subsequent radiative transfer within the visible and infrared spectral regions.

Consequently, the thermovision technique provides an effective non-contact approach for analyzing the temporal evolution of the explosive fireball, estimating its temperature regime, and reconstructing the characteristic energy-related parameters of the process [10], [11].

The temperature of detonation products for most conventional high-energy explosives typically ranges from approximately 3000 to 5000 K, depending on the chemical composition of the explosive, the fuel-to-oxidizer ratio, loading density, explosive geometry, and experimental conditions [10]. These values represent the thermodynamic characteristics of the system and should not be directly identified with the temperature reconstructed from the infrared radiometric signal.

For PBX-based explosive systems, published data indicate that the maximum fireball temperature is typically around 3600 K, representing the expected physical temperature range for comparison with and validation of the experimental results presented in this study [10], [11].

As with all radiometric measurement techniques, however, the recorded infrared signal does not represent the actual source temperature. Instead, it is the result of a thermal-radiative process governed by the source temperature, emissivity, detector spectral response, and atmospheric attenuation. Therefore, the actual fireball temperature can only be estimated using an appropriate inverse thermovision reconstruction model [1], [11].

Modern high-speed infrared thermovision systems enable time-resolved monitoring of explosive processes with high temporal resolution, allowing analysis not only of the maximum temperature but also of the complete temperature evolution of the fireball.

In the present study, the explosive process is characterized by the following parameters:
- maximum reconstructed fireball temperature, T_{max},
- time to reach the maximum temperature, t_{max},
- characteristic cooling rate, dT/dt;
- integral temperature response index,

$$E_I = \int_0^{t_{obs}} T(t)\, dt$$

which represents a relative measure of the overall thermal response during the observation period.

These parameters do not constitute a direct measure of the chemical energy released by the explosive. Instead, they provide a physics-based description of the temporal evolution of the thermal process and enable quantitative comparison of different explosive formulations using inverse thermovision reconstruction.

Table 2. Capabilities of the Thermovision Technique for Different Types of High-Energy Explosives

Explosive Type	Characteristic Temperature Range	Dominant Spectral Region	Principal Reconstructed Parameters
TNT	3000–4000 K	VIS + IR	T_{max}, cooling rate, fireball radius
PBX non-thermobaric	3200–3900 K	VIS + IR	Temperature field, cooling dynamics, energy distribution
Thermobaric mixtures	3000–5000 K	VIS + IR	Fireball duration, spatial temperature distribution, energy reconstruction

For TNT and other non-thermobarics, the temperature response originates from the short-lived emission of detonation products, whereas thermobaric formulations enable analysis of rapid temperature evolution and subsequent cooling. Unlike nuclear phenomena, these explosive systems are dominated by radiation within the visible and infrared spectral regions, making the thermovision technique suitable for monitoring the maximum temperature, cooling dynamics, fireball evolution, and the relative dynamics of thermal energy release (Table 2) [6-8].

4. INVERSE TEMPERATURE MODEL

An infrared thermovision camera does not measure the temperature of an observed object directly. Instead, it records a radiometric signal that depends on the surface temperature, material emissivity, atmospheric attenuation, the spectral characteristics of the optical system, and the temporal characteristics of image acquisition. Consequently, determining the actual temperature field constitutes an inverse problem, in which the temperature distribution is reconstructed from the measured infrared signal [1, 2].

The physical basis of the reconstruction is the law of thermal radiation. For the idealized case of total radiative emission, the Stefan–Boltzmann law can be expressed as

$$M = \varepsilon\, \sigma\, T^4$$

where M is the total radiative emittance, ε is the emissivity of the source, σ is the Stefan–Boltzmann constant, and T is the absolute temperature.

In a real measurement system, the recorded signal results from the interaction of the emitted radiation with the atmosphere, the optical system, and the detector. Therefore, temperature estimation requires the application of a correction and inverse reconstruction model, which can generally be expressed as

$$T_{max} = f(S_{IR}, \varepsilon, \tau, H(\lambda), t)$$

where S_{IR} is the measured infrared signal, ε is the emissivity, τ is the atmospheric transmittance, $H(\lambda)$ denotes the spectral response of the optical and detector system, and ttt is the acquisition time relative to the initiation of the process.

The proposed methodology is based on a physics-driven model that relates the spatial and temporal distribution of deposited energy to the resulting temperature field and the recorded infrared signal:

$$Q(x,y,z,t) \rightarrow T(x,y,z,t) \rightarrow M_\lambda(x,y,t) \rightarrow Sdet(t) \rightarrow T^*(x,y,z,t)$$

where $Q(x,y,z,t)$ denotes the volumetric heat source density, $T(x,y,z,t)$ is the temperature field, $M_\lambda(x,y,t)$ is the spectral radiance, $S_{det}(t)$ is the detector signal, and $T^*(x,y,z,t)$ is the reconstructed temperature field.

Unlike direct thermometry, temperature in thermovision is not a directly measured quantity but rather a parameter obtained through inverse thermovision reconstruction. Since this inverse problem is inherently ill-posed, its solution requires the incorporation of physical constraints, model assumptions, and appropriate regularization techniques to ensure stable and physically consistent reconstruction results [2, 9].

In addition to reconstructing the temperature field, the obtained results can be used to estimate the thermal energy loading of the investigated material. For this purpose, the accumulated specific thermal energy (thermal dose) is defined as

$$D = \int_0^t \frac{Q(x,y.z.\tau)}{\rho}\, dt$$

where D is the accumulated specific thermal energy (thermal dose) [J/kg], $Q(x,y,z,t)$ is the volumetric heat source density, i.e., the rate of energy deposition within the material [W/m^3], and ρ is the material density [kg/m^3].

Unlike conventional radiation dosimetry, this quantity represents the thermal energy dose, i.e., the amount of thermal energy accumulated per unit mass of the material

during the observation interval.

However, in explosive processes the spatial distribution of the heat source, $Q(x,y,z,t)$, cannot be determined directly from infrared measurements because the recorded signal represents the outcome of a complex thermal-radiative process. Consequently, the inverse thermovision reconstruction model is primarily employed to recover the spatiotemporal temperature evolution, while the corresponding energy-related parameters are derived from characteristic quantities extracted from the reconstructed temperature response.

5. EXPERIMENTAL RESULTS

5.1. Experimental Setup and Parameters

Experimental investigations were conducted on six explosive charges, each with a mass of 1 kg, prepared in three different PBX formulations (PBX-1, PBX-2, and PBX-3). Two independent experiments were performed for each formulation to evaluate the repeatability of the reconstructed temperature response.

The samples were designated as PBXij, where the first index (i=1,2,3) denotes the formulation type, while the second index (j=1,2) identifies the repeated measurement.

Measurements were performed using a high-speed infrared thermovision camera operating at 1466 Hz, equipped with a 50-mm focal-length lens and positioned at a distance of 60 m from the explosive charge. The resulting spatial resolution was approximately 36 mm/pixel, enabling continuous monitoring of the temporal evolution of the fireball throughout the explosive event.

From the reconstructed temperature–time histories, the following characteristic parameters were extracted:
- maximum reconstructed fireball temperature, T_{max};
- time to reach the maximum temperature, t_{max};
- characteristic cooling rate, $(dT/dt)_{cool}$;
- integral temperature response index, E_I.

These parameters were used to compare different PBX formulations based on their thermal-radiative response.

5.2. Analysis of the Temperature–Time Response

For each experiment, the following characteristics were analyzed:
- the reconstructed temperature evolution, $T=T(t)$;
- the maximum reconstructed temperature, T_{max}, corresponding to the highest temperature attained by the fireball during the explosive process;
- the cooling rate, $(dT/dt)_{cool}$, evaluated after the temperature peak as the slope of the descending portion of the temperature curve.

The cooling rate is governed by several simultaneous energy dissipation mechanisms, including:
- thermal radiation;
- convective heat transfer;
- expansion of detonation products;
- mixing with the surrounding air.

To provide an additional measure of the overall thermal response, the integral temperature response index was introduced:

$$E_I = \int_0^{t_{obs}} T(t)\,dt$$

which represents a relative measure of the accumulated temperature response during the observation interval.

It should be emphasized that E_I does not represent the actual chemical energy released by the explosive. Instead, it is an integral parameter derived from the reconstructed temperature signal, enabling quantitative comparison of different explosive formulations based on their thermal response.

In practical data processing, the discrete form was employed:

$$E_I = \sum_{i=1}^{n} T_i \Delta t$$

where T_i is the reconstructed temperature in the i-th frame, nnn is the total number of analyzed frames, and

$$\Delta t = 0{,}682\ ms.$$

5.3. Statistical Analysis

Two independent measurements were performed for each PBX formulation to evaluate the repeatability and variability of the experimental response.

The following statistical parameters were determined:
- individual values of the maximum reconstructed temperature, T_{max};
- mean temperature, $\bar{T}$;
- standard deviation, σ_T ;
- indicative confidence interval.

The mean value for each formulation was calculated as

$$\bar{T}_j = \frac{1}{n_j}\sum_{i=1}^{n_j} T_{ij}$$

where T_{ij} denotes the maximum reconstructed temperature obtained in the i-th experiment of formulation j.

The standard deviation was calculated as

$$\sigma_{T_j} = \sqrt{\frac{\sum_{i=1}^{n_j}\left(T_{ij} - \bar{T}_j\right)^2}{n_j - 1}}$$

To estimate the uncertainty of the mean value, a 95% confidence interval (used here as an indicative interval of variation) was determined using Student's t-distribution:

$$CI_{95} = \bar{T}_j \pm t_{0{,}975,n_j-1}\frac{\sigma_{T_j}}{\sqrt{n_j}}$$

Table 3. Statistical Parameters of the Maximum Reconstructed Temperature for the Investigated PBX Formulations

Formulat.	Sam. 1	Sam. 2	Mean (K)	SD (K)	95% CI (K)
PBX-1	2044.38	2030.87	2037.63	9.55	±85.83
PBX-2	2057.49	3090.05	2573.77	730.13	±6559.85
PBX-3	2255.55	2101.93	2178.74	108.63	±975.95

The results presented in Table 3 reveal different levels of variability among the investigated formulations. PBX-1 exhibits the highest repeatability, whereas PBX-2 shows substantially greater dispersion owing to the large difference between the two repeated measurements. PBX-3 demonstrates an intermediate level of variability.

Considering the limited number of repeated experiments (n=2), the calculated statistical parameters should be interpreted as indicators of experimental variability rather than as definitive estimates of the underlying statistical distribution.

The reconstructed temperatures fall within the physically expected range for RDX/HMX-based high-energy explosive systems, supporting the physical consistency of the applied radiometric reconstruction model [10].

The obtained results demonstrate that the thermovision technique enables effective characterization of the temporal evolution of the fireball and extraction of parameters sensitive to differences in the chemical composition of PBX formulations.

The principal limitations of the proposed methodology arise from the variable emissivity of the fireball, the spectral response of the detector, atmospheric attenuation, and the finite spatial and temporal resolutions of the measurement system. Nevertheless, the results confirm that inverse thermovision reconstruction provides a reliable and physically meaningful approach for the comparative characterization of the thermal response of different high-energy explosive systems.

6. CONCLUSONS

The capabilities and limitations of thermovision techniques for the characterization of transient high-energy explosive processes were investigated. An inverse thermovision reconstruction approach was developed using a physics-based radiometric model that relates the measured infrared signal to the reconstructed temperature–time evolution of the fireball.

Experimental analysis of PBX formulations demonstrated that thermovision techniques enable the extraction of characteristic thermal-response parameters, including the maximum reconstructed temperature, peak-time, cooling rate, and integral temperature index. The reconstructed temperatures were within the expected range for RDX/HMX-based high-energy systems, confirming the physical consistency of the proposed model and reconstruction procedure.

The analysis of nuclear explosive phenomena showed that conventional infrared systems are limited during the initial fireball phase due to dominant high-energy X-ray and ultraviolet radiation, while thermovision-based characterization becomes applicable during later evolution stages.

The obtained results confirm that thermovision techniques combined with physics-based radiative transfer models and inverse reconstruction methods provide an effective non-contact approach for the analysis and comparative characterization of conventional high-energy explosive systems.

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