Dynamic ignition regime of condensed system by radiate heat flux

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Abstract. The main ignition characteristics of high-energy materials are the ignition time and critical heat flux allowing evaluation of the critical conditions for ignition, fire and explosive safety for the test solid propellants. The ignition process is typically studied in stationary conditions of heat input at constant temperature of the heating surface, environment or the radiate heat flux on the sample surface. In real conditions, ignition is usually effected at variable time-dependent values of the heat flux. In this case, the heated layer is formed on the sample surface in dynamic conditions and significantly depends on the heat flux change, i.e. increasing or decreasing falling heat flux in the reaction period of the propellant sample. This paper presents a method for measuring the ignition characteristics of a high-energy material sample in initiation of the dynamic radiant heat flux, which includes the measurement of the ignition time when exposed to a sample time varying radiant heat flux given intensity. In case of pyroxyline containing 1 wt. % of soot, it is shown that the ignition times are reduced by 20–50 % depending on the initial value of the radiant flux density in initiation by increasing or decreasing radiant heat flux compared with the stationary conditions of heat supply in the same ambient conditions.

1. Introduction

The features of ignition of condensed substances by means of heating with the external heat flux (conductive, convective, radiant or mixed) are required to develop initiating explosives systems and high-energy materials, to assess fire and explosive features of substances and to solve a number of other practical problems. In this paper, the ignition is a stationary self-sustaining combustion mode after the termination of an external heat flux [1].

At present time, the characteristics of ignition during constant heating by heat flux in the so-called static heating mode are being studied [1, 2]. In real conditions, in particular at the ignition of solid propellant rocket engine [3], combustible materials under fire conditions [4, 5] and etc., the ignition is carried out through heating by heat flux in a dynamic mode, which depends on time.

A theoretical analysis of the dynamic mode of ignition is conducted mainly through a thermal solid-phase model. In this case, the formation of the heated layer in the condensed phase takes place in complicated dynamic conditions, whereby the ignition delay time substantially depends not only on the heat flux density to the sample, but also on the mode of changes in the heat flux induction period [1, 2, 5–9].

IOP Conf. Series: Journal of Physics: Conf. Series **830** (2017) 012136 doi:10.1088/1742-6596/830/1/012136

An experimental research in characteristics of ignition condensed substance by exposure to radiant heat flux is carried out in most of the works with constant heat flux in the induction period [10-17]. Dynamic ignition modes with convective and radiant heat flux in the available literature have been considered in single publications [4, 18-21], apparently, due to the technical complexity of the correctly set experiments.

In [18, 19], the results of ignition of polyvinyl nitrate and pyroxyline are presented. These samples were lit when exposed to the increasing and decreasing convective heat flux created by gaseous products of combustion in a combustion chamber with a nozzle. Due to the large spread of the experimental data on ignition delay time (up to 60%), only quality ignition characteristics were obtained in these studies.

The results of measurements of ignition characteristics for pyroxyline [20, 21] and for timber [4], when exposed to dynamic mode of the heat flux, showed that the same values of the heat flux density for the ignition delay t_{ign} differ for static and dynamic modes of heating.

In these studies in the analysis of experimental data, an average heat flux for dynamic modes of heating was used:

$$\overline{q} = \frac{1}{t_{ign}} \cdot \int_{0}^{t_{ign}} q(t)dt\,, \tag{1}$$

where $\overline{q}$ is the average value of the variable heat flux density $q(t)$ of the induction period t_{ign}.

As noted in [10], it does not take into account fully the dynamics of change in the temperature profile in the condensed phase. The generalization of the experimental data on the dynamic modes of ignition [4, 18-21] is difficult due to component composition of the samples of condensed systems, methods of research and conditions of the experiment.

The aim of this work is the experimental study of the characteristics of pyroxyline ignition under dynamic modes as a model substance with the known thermal and kinetic characteristics when heated by thermal radiation. To correctly analyze the ignition characteristics, the experiments were carried out in strictly identical conditions using a single methodology for continuous, increasing and decreasing heat flux.

2. Experiment

The experiments were carried out using an optical furnace "Uran-1" [10]. The emitter of the setup consists of an elliptical mirror and a DKsR-10000 xenon lamp (Figure 1) with a nominal heat output of 5.5 kW with radiation A = 0.25–1.85 μm (Figure 2). The influence of the variable heat flux on the delay time of ignition of pyroxyline in the air at atmospheric pressure was studied. The distribution of the radiation in the spectral ranges was as follows: 0.5 kW (9%) in the ultraviolet spectral range, 2 kW (36%) in the visible range, and 3 kW (55%) in the infrared range. The integrated radiant flux (in a broad range of wavelengths) from the DKsR-10000 xenon lamp of Uran-1 was focused by an elliptical mirror into a spot 12 mm in diameter. This capacity corresponds to the integral blackbody radiation at a temperature of 3110 K.

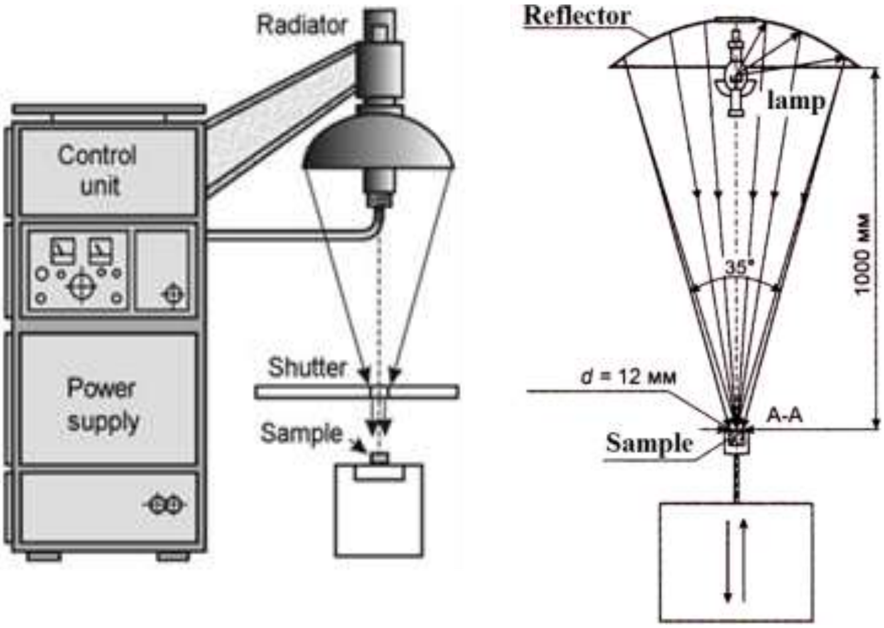

Figure 1. Optical scheme of installation of the integral radiant heat "Uran-1"

In the research, a metal mesh placed perpendicular to the optical axis of the elliptical reflector at a distance of 30–40 cm from the focal plane was used to weaken the power of the radiation. The strength of the current and voltage supplied to the xenon lamp were reduced. The flux density was measured by calorimetry with a relative error not exceeding 10%. We used a copper calorimeter as a disk 10 mm in diameter and 3 mm thick. The surface of the disk that absorbs radiation was covered with lamp black.

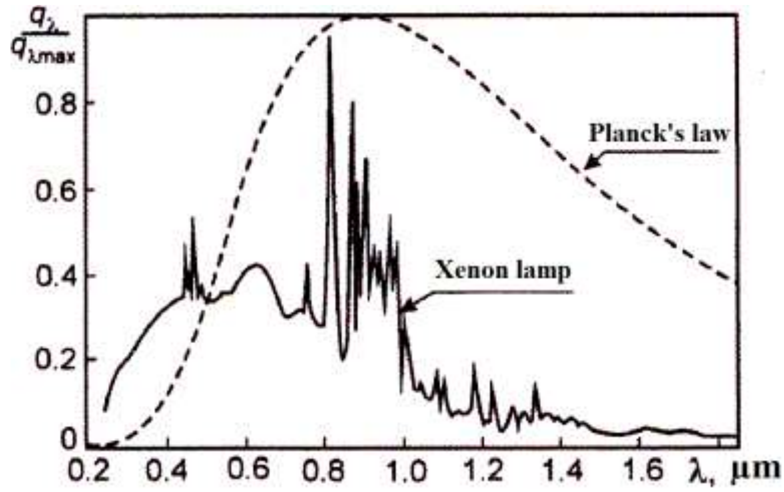

Figure 2. The distribution of the spectral irradiance of the DKsR-10000 xenon lamp and a black body at 3110 K

The pyroxylin samples containing 1 wt. % of carbon black K-354 were used as a model. Carbon black is added to reduce the influence of the optical parameters of the heat source. The diameter and height of the samples was 10 mm, and the density was 1.45 g/cm^2.

The signal of the ignition delay time was recorded by the photodiode FD-9 at the first appearance of flame. When the ignition electrical signals from the photodiodes were recorded by oscilloscope OWON, the data were saved. Indications of the difference between the two signals on the oscilloscope match the ignition delay time.

A dynamic heat flux mode is ensured by moving the test sample while it is heated by radiation heat flux along the optical axis of the elliptical reflector, experimental facility "Uran-1". For this purpose, we used an electromechanical device allowing the sample to move at a speed of 4.75 cm/s The dynamic regime was carried out with a speed of movement of the sample.

In order to make clear the heat flux distribution function the density of heat flux at three or four fixed points on the optical axis of the setup was determined before each measurement of the ignition delay time of pyroxyline. The heat flux density was measured using a micro calorimeter installed in the place of the test sample [7]. The accuracy of the heat flux density measurement does not exceed 10%. Based on the known speed of movement of the sample along the optical axis, it is possible to determine the dynamics of the heat flux density in this experiment.

According to the obtained values of ignition delay time of VEM at different radiation flux, the move distances of the samples at the moment of ignition were calculated. Calibration of measuring the heat flux density of the system by moving the test pyroxylin sample relative to the focal plane of the radiator was carried out in static conditions. A heat flux sensor was placed in the focal plane ($f \approx 1$ m), the exact coordinate of which is determined by the maximum sensor readings ($q = q_f$) for a given supply current value of the xenon lamp and was taken as $x = 0$.

Then the heat flux sensor was moved along the optical axis of the apparatus in the direction from the emitter, and the heat flux density at several fixed points $x_i > 0$ along the coordinate x was measured. Similar measurements were performed to move the sensor of the heat flux toward the emitter. The resulting averaged tabular dependence of $q_i(x_i)$ was approximated by exponential function

$$\overline{q}(x) = \frac{q(x)}{q_f} = \exp(-bx)\,, \tag{2}$$

where $q(x)$ is the heat flux density at distance x from the focal plane; q_f is the heat flux density in the focal plane ($x = 0$).

Figure 3 shows a generalized dependence obtained in the range of $x = (0 \div 17.5)$ cm, = (10.2 ÷ 121.2) W/cm^2 (coefficient of determination $R^2 = 0.9865$):

$$\overline{q}(x) = \exp(-0.239x) \tag{3}$$

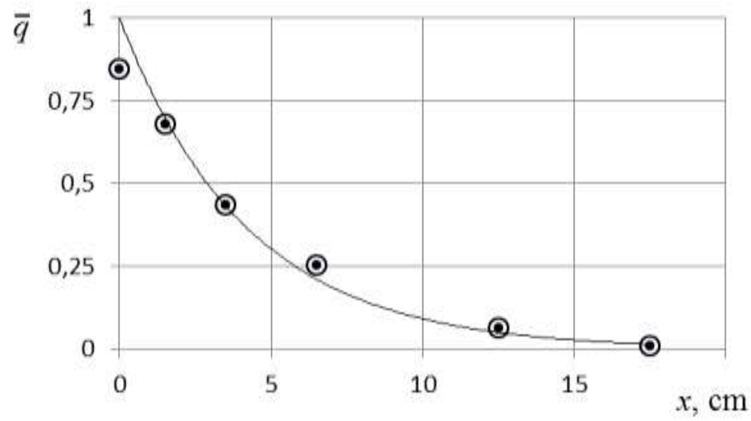

Figure 3. Dependence of $\overline{q}$ on the focal plane distance of the sample

To determine the dynamics of the measurement, the time dependence of the heat flux density (2) can be converted to $\overline{q}$ mean (t), substituting $x = ut$, where u is the displacement speed of the sample relative to the focal plane of the radiator.

When you move the sample from the focal plane in the direction from the emitter (decreasing heat flux)

$$\overline{q}(t) = \exp(-but) \tag{4}$$

and (increasing heat flux) during the reverse movement of

$$\bar{q}(t) = \exp\left[-b(x_0 - ut)\right] \tag{5}$$

Here x_0 is the coordinate of the sample at the initial time $t = 0$.

The dependence of $q(t)$, calculated according to the equations (3), (4) for the conditions of the experiments (u = const = 4.75 cm, x_0 = 17.5 cm, b = 0.239), is shown in Figure 4.

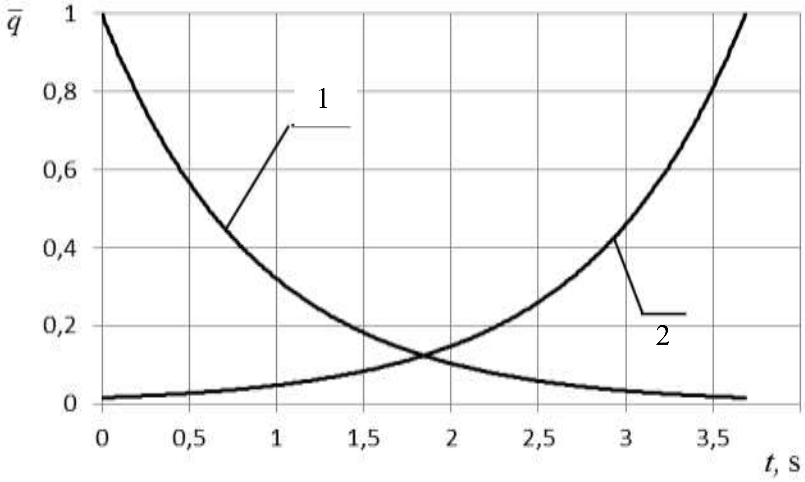

Figure 4. Dependencies $\bar{q}(t)$ for decreasing (1) and increasing (2) heat flux

The movement of the sample from $x = 0$ to x_0 = 17.5 cm and reverse movement from x_0 = 17.5 cm to $x = 0$ was

$$t_0 = x_0/u = 3.684 \text{ s.}$$

3. Experimental results

The experiments were conducted in conditions of increasing heat flux. The experiments differed in the rate of change in the heat flux density during ignition of pyroxylin. The results of the study are shown in Table 1, where a, b are the coefficients of the approximation function, Q is calculated by equation (2). The average values of the heat flux and change in flux $(dq/dt)_{med}$ during the induction period were determined by formulas

$$\tilde{q} = \frac{Q}{t_{ign}}, \quad (dq/dt)_{\text{med}} = \frac{1}{t_{ign}}\left[q(t_{ign}) - q(0)\right]$$

Table 1. Ignition characteristics of pyroxylin with increasing heat flux

Interval q, W/cm^2	a, W/cm^2	b, s^{-1}	t_{ign}, s	Q, J/cm^2	q,W/cm^2	$(dq/dt)_{\text{med}}$, W/(cm^2·s)
0.21÷10.50	0.21	1.27	3.08±0.04	8.10	2.63	3.34
0.51÷16.47	0.51	1.25	2.78±0.08	12.77	4.59	5.74
0.99÷19.00	0.99	1.66	1.78±0.06	10.85	6.10	10.12
1.78÷21.24	1.78	1.71	1.45±0.01	13.42	7.85	13.42

Experimental data [1] on pyroxylin ignition characteristics at a constant heat flux q_0 are given in table 2. The value of Q was calculated by the formula

$$Q = q_0 \cdot t_{ign}.$$

Table 2. Ignition characteristics of pyroxylin with constant heat flux

q_0, W/cm^2	t_{ign}, s	Q, J/cm^2
3.61	9.1	32.85
5.43	4.06	22.05
13.55	0.70	9.48
17.83	0.42	7.49

Comparison of the characteristics of ignition pyroxylin obtained with increasing heat flux with the experimental data at constant heat flux [11] is shown in Figure 5.

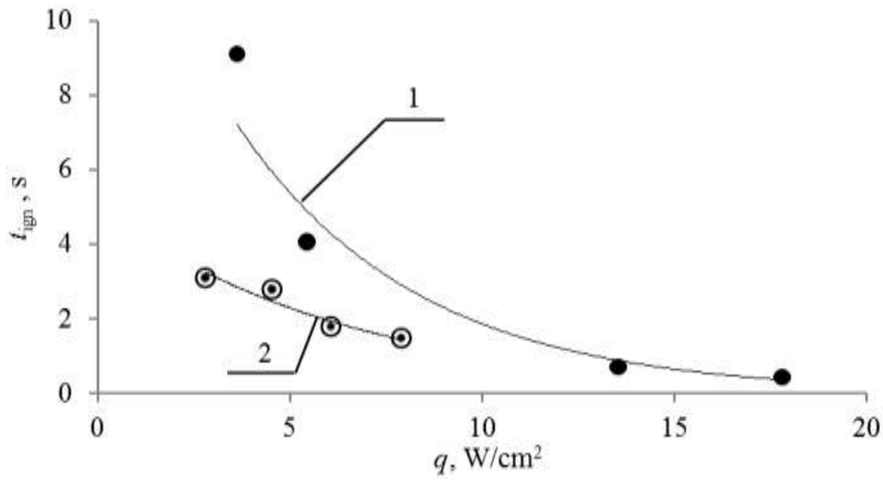

Figure 5. The ignition delay time vs. heat flux density at constant (1) and increasing (2) heat flux

From graphs in figure 5, it is seen that in the studied range q of ignition delay time of pyroxylin at increasing heat flux with an average value is smaller than that at a constant heat flux. With increasing heat flux density, the ignition delay time difference decreases and asymptotically tends to zero when $q > 8$ W/cm^2.

The dependence of the amount of thermal energy Q obtained by means of pyroxylin during the period on the heat flux density in heating with constant (1) and increasing (2) heat flux is shown in figure 6.

In heating the sample with constant heat flux, Q drastically decreases with increasing q_0, and in heating with increasing heat flux, growing dependence $Q(\overline{q})$ is observed. The same kind of Q is dependent on the average rate of the change in the heat fux $(dq/dt)_{med}$ shown in Figure 7.

This effect is apparently due to the particularities of formation of the heated layer of condensed phase in static and dynamic conditions of ignition of pyroxylin..

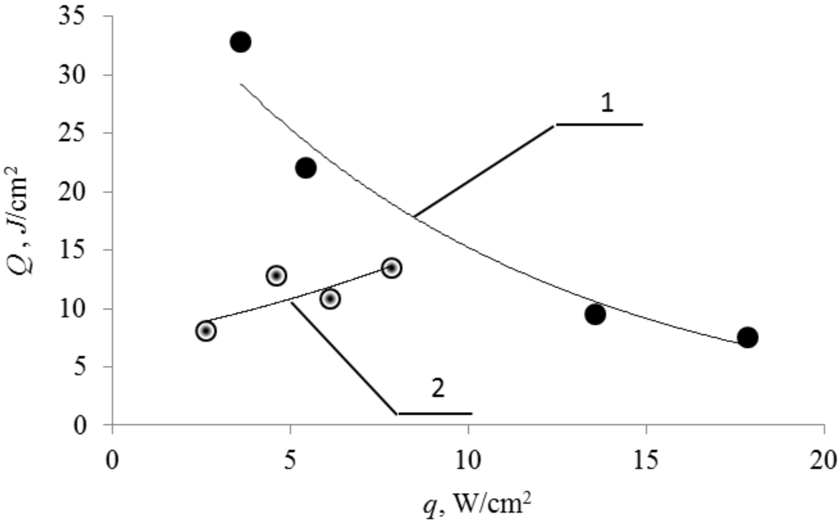

Figure 6. The dependence of energy on the heat flux density at constant (1) and increasing (2) heat flux

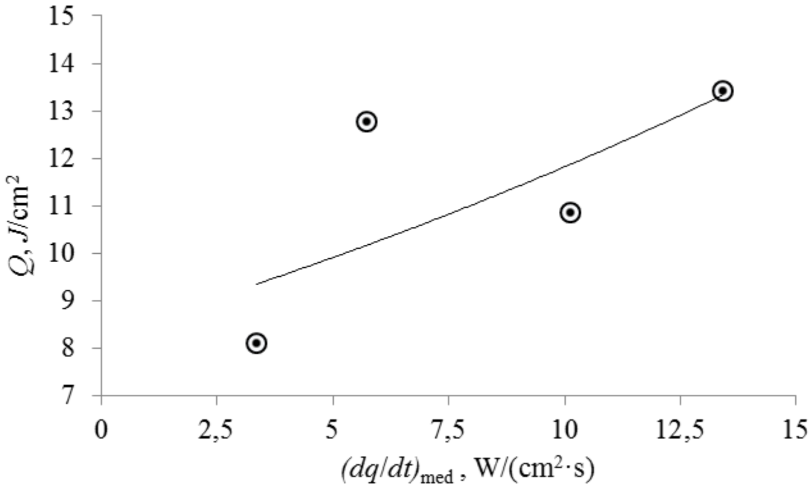

Figure 7. Dependence of energy on the average rate of the heat flux density change

4. Conclusion

A method for measuring the ignition characteristics of high-energy material samples when exposed to dynamic regime radiant heat flux, which includes the measurement of the ignition delay time during exposure of the sample surface to time varying radiant heat flux with the given intensity, was presented. The results of the experimental study of ignition of pyroxyline in heating with increasing radiation flux in the range of (0.2 ÷ 22) W/cm^2 have been presented. The findings suggest that pyroxylin containing 1 wt. % of soot in dynamic heating regime is higher than that in static conditions in the studied range of the heat flux density. It was found that the ignition times are reduced by 20–50 % depending on the initial value of the radiant flux density in initiation by increasing or decreasing heat flux compared with the stationary conditions of heat supply under the same ambient conditions.

Acknowledgement

This work was supported by the Ministry of Education and Science of the Russian Federation under Agreement No. 14.577.21.0157 of 11.28.2014 (unique identifier RFMEFI57714X0157).

IOP Conf. Series: Journal of Physics: Conf. Series **830** (2017) 012136 doi:10.1088/1742-6596/830/1/012136

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