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PHYSICS

A Criterion for Detonation Initiation in Gas Mixtures

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INTRODUCTION

Constructing critical conditions for detonation initiation is one of the basic aspects in the theoretical description of pulsed-detonation processes and of the passage from rapid consumption (deflagration) to detonation. Presently, in the majority of cases, approaches based on the concept of detonation critical energy are used [1–4]. Many experimental studies are also devoted to the analysis of the detonation initiation under the action of the electric discharge in gas media. For example, in the experiments described in [1], the detonation initiation in the stoichiometric hydrogen–oxygen mixture under the action of the electric discharge was investigated.

In this study (see data presented by dots in Fig. 1), the minimum critical energy E_{cr} was measured that should be released inside a volume to be demolished to initiate the detonation. Under the conditions of these experiments, there existed a certain characteristic time t_{mix} such that for electric discharges of the duration $t_f < t_{mix}$, the critical energy E_{cr} was independent of the discharge duration and had the constant value E_0. Thus, E_0 is the minimum energy for the detonation of a mixture to be demolished. The authors of [1] defined the quantity t_f as the time between the instants of the load application and of the maximization of the average power $(E(t)/t))_{max}$ introduced into the medium. For $t_f > t_{mix}$, the critical energy E_{cr} that should be released inside the volume to be demolished increases with the duration of the action initiating the detonation.

Based on the results presented in [1] and obtained in preceding experiments, the authors concluded that the time t_f is the basic characteristic of the electric discharge initiating detonation in gas media and stated that the energy transferred to the medium upon the instant of the maximum average power had been attained could not affect the direct detonation initiation.

Unfortunately, at present, there is no model capable of explaining the phenomena observed for an arbitrary method of the power supply. Therefore, the physical sense of the quantity t_{mix} remains unclear. In order to explain the phenomena observed, we introduce here a new criterion for detonation initiation in gas mixtures, which is based on measurable parameters of the medium.

ENERGY CRITERION FOR DETONATION INITIATION

In order to determine conditions for detonation initiation in gas mixtures, we propose a criterion based on the concept of the incubation time for the process of

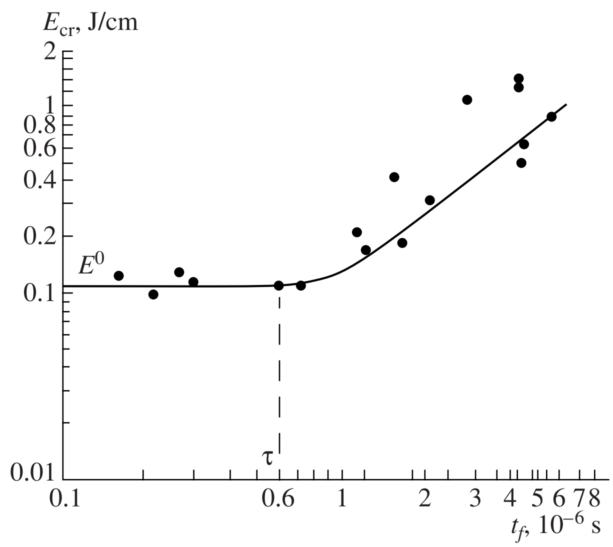

Fig. 1. Critical energy of the detonation initiation as a function of the maximization time t_f for the average power supply: (solid line) the proposed energy criterion and (dots) experimental data of [1].

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direct detonation initiation. This criterion is as follows:

$$\frac{1}{\tau}\int_{t-\tau}^{t} U(s)ds \le U_c, \tag{1}$$

where $U(t)$ is the power (i.e., the energy transfer rate) delivered to the detonating mixture and τ is the incubation time inherent in the development of the direct detonation process. The latter quantity that characterizes the detonating medium is determined experimentally. It is independent of the parameters (frequency, discharge duration, etc.) of the action applied. The quantity U_c is the critical rate of the power supply to the mixture to be demolished, and t and s are the global and local times, respectively.

The criteria of such a kind turned out to be rather useful for the description of various dynamic transient processes such as dynamic brittle fracture [5–8], dynamic yielding of metals [9], phase transitions in the case of high-rate methods of the power supply [10], cavitation [11], and electric breakdown [11]. We emphasize once more that U_c and τ are independent of the method of power supply and are determined by both the mixture composition and the external parameters (pressure etc.). The instant of time t_* when criterion (1) transforms into the equality corresponds to the attainment by the medium of the critical state, which will be finished exactly by the direct-detonation initiation in the medium being loaded (i.e., a steady detonation wave will be formed).

Then critical rate U_c corresponds to the minimum rate of the power supply, which is capable of initiating the detonation in the mixture being studied. When the rate of the power supply is smaller than U_c, the formed unsteady overcompressed detonation wave fails to attain the steady-propagation regime.

The incubation time of the detonation process is directly connected with the processes preceding the attainment of the steady regime for the detonation-wave propagation, including chemical processes. The time τ is defined as the time interval between the start of the power-supply process ($t = 0$) and the time of the attainment by the medium of the state that will be obligatorily finished by the formation of the steady detonation wave when the rate of the power supply to the medium to be demolished is U_c.

As is seen from (1), if the energy required to form the steady detonation wave is delivered for the time $t_* < \tau$, then all the delivered energy is spent to initiate the detonation. Therefore, for $t_* < \tau$, the critical energy E_{cr} is independent of t_*, which is consistent with the experimental results of [1]. Thus, it becomes clear that, under the conditions of the experimental studies of [1], the measured time t_{mix} coincides with the incubation time τ of the detonation initiation process.

APPLICATION OF THE ENERGY CRITERION TO ESTIMATE DETONATION CONDITIONS IN GAS MIXTURES

We now use the criterion introduced to estimate the detonation conditions in the experiments described in [1]. In these experiments, the detonation in the stoichiometric hydrogen–oxygen mixture was initiated by electric discharges of different frequencies and amplitudes up to the detonation wave had been formed. The energy of such a discharge, which was transferred to the mixture to be demolished for a time t can be presented by the following expression:

$$E(t) = \int_0^t i^2(t)Rdt, \tag{2}$$

where R is the electrical resistance of the discharge gap, i is the electric current in the circuit, and t is time. We can approximate the history of attenuating electric discharge oscillations under the conditions of the experiments described in [1] by the expression

$$i(t) = Ae^{-at}\sin(\omega t),$$

where A is the amplitude, a is the attenuation coefficient, and ω is the discharge current oscillation frequency. In this case, condition (1) takes the form

$$\frac{1}{\tau}\int_{t-\tau}^{t} A^2 e^{-2as}\sin^2(\omega s)Rds \le U_c. \tag{3}$$

For the given discharge frequency ω, the minimum amplitude necessary to initiate the detonation can be found from the condition

$$\max_t \varepsilon(t) = U_c, \tag{4}$$

where

$$\varepsilon(t) = \frac{1}{\tau}\int_{t-\tau}^{t} A^2 Re^{-2as}\sin^2(\omega \cdot s)ds.$$

From an analysis of the experimental data (dots in Fig. 1), we can obtain both the quantity E^0 (i.e., the minimum value of the critical energy required to initiate the detonation) and the incubation time τ. As was discussed previously, the incubation time τ coincides with the measured time t_{mix}. Using the minimum critical energy E^0 and the incubation time τ, we can find the critical rate of the power supply

$$U_c = \frac{E^0}{\tau}. \tag{5}$$

Upon substituting the above-determined quantities τ and U_c into (4), we find the threshold amplitude A. Further, using (2), we can determine the critical energy E_{cr} of the detonation initiation as a function of time t_*

before the formation of the critical state leading to the detonation initiation. The dependence thus obtained is shown in Fig. 2.

As was emphasized by the authors of [1], under their experimental conditions, time t_* coincides with time t_f corresponding to maximization of the average power load transferred to the medium. Thus, we may conclude that for the experimental conditions of [1], the results presented in Fig. 2 are rather well consistent with the values of the critical energy obtained in [1]. Nevertheless, criterion (1) allows us to additionally calculate the critical energies that lead to the detonation of the gas medium under the action of pulsed loads of duration t_f. This is done with the goal of absolutely correct comparison of the calculation results with the experimental data of [1]. In Fig. 1, the calculation results exploiting the new detonation criterion are compared with the experimental data of [1].

Figure 1 shows that the model proposed based on criterion (1) makes it possible to describe sufficiently precisely the experimentally observed detonation effects in gas mixtures.

As was already indicated above, the quantities U_c and τ are the parameters defining the properties of the detonating mixture rather than the properties of the experiment. One of the possible methods to determine U_c and τ is a series of experiments devoted to detonation initiation by discharges of over-threshold amplitudes. In the case of the delivery for time $t_* < \tau$ of the energy required to form the detonation, the initiating energy attains the minimum critical energy E^0. In contrast, for $t_* > \tau$, the initiation energy increases with t_*. This allows us to determine τ, whereas U_c is calculated from (5).

Thus, we have proposed a new simple criterion that makes it possible to estimate conditions for detonation initiation in gas media. The model is based on characteristics (critical rate U_c of the power supply and incubation time τ) of the medium to be demolished, which are extracted from experimental data and allow the behavior of the given mixture to be predicted for an arbitrary action.

Introducing the incubation-time concept with the goal to estimate the conditions of detonation initiation clearly demonstrates the effect of the history of the power supply in a certain finite volume of a mixture to be demolished on the processes occurring in this volume.

It seems that similar criteria can be applied to determine ultimate conditions for the detonation of liquid and solid explosives.

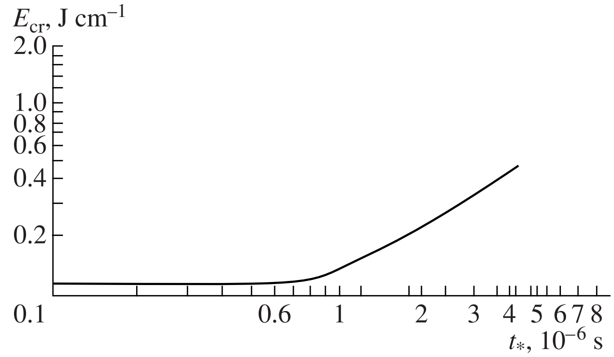

Fig. 2. Critical energy of the detonation initiation as a function of time t_* required for the mixture to attain the critical state according to the proposed energy criterion.

One possible application of the new criterion is development of the so-called pulsed detonation engines (PDEs).

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REFERENCES

1. R. Knystautas and J. H. Lee, Combust. Flame, No. 27, 221 (1976).
2. V. A. Levin, T. A. Zhuravskaya, V. V. Markov, and S. F. Osinkin, Khim. Fiz. **23** (9), 52 (2004).
3. V. A. Levin, V. V. Markov, S. F. Osinkin, and T. A. Zhuravskaya, Fiz. Goreniya Vzryva, No. 6, 96 (2002).
4. A. A. Vasil'ev, *Proceedings of the European Combustion Meeting (2005)*.
5. N. F. Morozov, Yu. V. Petrov, and A. A. Utkin, Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela, No. 5, 180 (1988).
6. Y. V. Petrov, N. F. Morozov, and V. I. Smirnov, Fatigue Fracture Eng. Mater. Struct., No. 26, 363 (2003).
7. V. Bratov and Y. Petrov, Intern. J. Solids Struct. **44**, 2371 (2007).
8. V. Bratov and Y. Petrov, Intern. J. Fracture **147**, 53 (2007).
9. A. A. Gruzdkov and Yu. V. Petrov, Dokl. Phys. **44**, 114 (1999) [Dokl. Akad. Nauk **364**, 766 (1999)].
10. Yu. V. Petrov and E. V. Sitnikova, Dokl. Phys. **50**, 88 (2005) [Dokl. Akad. Nauk **400**, 480 (2005)].
11. Yu. V. Petrov, Dokl. Phys. **49**, 246 (2004) [Dokl. Akad. Nauk **395**, 621 (2004)].

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