ЕҢБЕК ҚЫЗЫЛ ТУ ОРДЕНДІ
«Ә. Б. БЕКТҰРОВ АТЫНДАҒЫ
ХИМИЯ ҒЫЛЫМДАРЫ ИНСТИТУТЫ»
АКЦИОНЕРЛІК ҚОҒАМЫ

ҚАЗАҚСТАННЫҢ ХИМИЯ ЖУРНАЛЫ

ХИМИЧЕСКИЙ ЖУРНАЛ КАЗАХСТАНА

CHEMICAL JOURNAL of KAZAKHSTAN

АКЦИОНЕРНОЕ ОБЩЕСТВО
ОРДЕНА ТРУДОВОГО КРАСНОГО ЗНАМЕНИ
«ИНСТИТУТ ХИМИЧЕСКИХ НАУК
им. А. Б. БЕКТУРОВА»

2 (66)

АПРЕЛЬ – ИЮНЬ 2019 г.

ИЗДАЕТСЯ С ОКТЯБРЯ 2003 ГОДА

ВЫХОДИТ 4 РАЗА В ГОД

АЛМАТЫ
2019

UDC 621.45.048

ZH. K. YELEMESSOVA[1,*], *Z. A. MANSUROV*[1,2], *B. T. LESBAYEV*[1,2], *R. SHEN*[3]

[1]Al-Farabi Kazakh National University, Almaty, Republic fd Kazakhstan,
[2]Institute of Combustion Problems, Almaty, Republic of Kazakhstan,
[3]Nanjing University of Science and Technology, Nanjing, China

LASER IGNITION OF ENERGETIC MATERIALS BASED ON CARBON CONTAINING METAL OXIDE PROPELLANT

Abstract. An experimental study to investigate the laser ignition using a diode laser for carbon containing energetic compositions based on metal oxide propellant in order to develop more liable and greener laser ignitors for directinitiation of the propellantwas conducted. Samples of the propellant were ignited using a 974 nm near-infrared diode laser. Laser beam parameters including laser energy, beam width and pulse width were investigated to determine theireffects on the ignition performance in terms of delay time, rise time and burn time of the propellant which wasarranged in several different configurations. The results have shown that the smaller beam widths, longer pulsewidths and shorter laser energy resulted in shorter ignition delay times and overall burn times, however, which increasing the amount of laser energy transferred to the material resulted in no significantreduction in either delay time or overall burn time. The tested propellant well responded to laser ignition, an expansion that supports continued research into the development of laser-based propellant ignitors.

Key words: laser ignition, ignition delay, combustion, energy materials, activated carbon, metal oxide.

Introduction. In recent years efforts have been made to eliminate primary-explosives from ignition mechanisms, primarily because of the associatedsafety and environmental hazards. Historically, several accidentshave resulted from the use of high explosive materials, which canbecome unpredictable if they are not carefully stored and monitored.For example, high temperatures experienced during storageareknownin affecting the energetic materials service life and, in extreme cases, lead to potentially fatal occasions. Governments around the world have introduced measures to discourage the use of heavy metals inignitors and other explosive devices with the introduction of newlegislation, such as REACH. This has meant that the search foralternative solutions has become not only desirable, but necessary. Direct ignition of energetic materials using laser technology couldeliminate the problems associated with traditional ignitors, by removingthe primary explosives and heavy metals [1-3].

Laser ignition offers several advantages over electrical ignitionmechanisms, including immunity to electromagnetic interference, nometal component insertion, the reliability and reproducibility inherentof laser systems and the ease with which the optical fibers could beutilized to install multipoint initiation. It has become an important andinteresting topic not only to researchers, but for manufacturers ofexplosive ignitors, due to the modern advancements in the developmentof lasers which are more compact, more cost effective, and moreefficient in comparison to those lasers used during the first laserignition attempts in the 1960's [4-7]. Despite the extensive researchwhich has been carried out into the laser ignition of energetic materialsincluding propellants [13–15], few laser-based ignitors havebeen developed for real world use to date and the details of these systems are not currently available in the open literature.

Many energetic materials that are typically used in low energy electro-explosive devices (EED's) can be ignited whenheated by a laser of sufficient power density. In the past decade, high-power solid-state laser diode technology hasmatured to the point that it is a viable candidate for replacement of EED's in applications where reliability and safety areconcerns [8]. Historically, the development of optical initiators has been based on off-the-shelf laser diodes and solid state lasers. In order to reverse this trend and optimize the laser source specifically for ignition of energetic materials, thefundamental process of ignition must be better understood. In this work we analyze the thermal-radiative transport inenergetic materials that are being heated by a laser beam, and investigate the effects of material properties and laserbeam shape on the minimum energy threshold for ignition.

Since the laser was first introduced as an ignitionsource for energetic materials numerous studiesinvolving laser ignition of both deflagrationand detonation have been carried out and published. However, none or only a few studies have been devoted to diode laser ignition of unconfined secondaryexplosives by means of an optical fiber. Thereare at least two possible reasons for this apparently weakinterest. The first possibility is that studies of the ignitionof confined explosives are more useful when constructinglaser ignition systems. The second possibility originatesfrom the earlier shown strong pressure dependence inthe threshold ignition energy. The energy needed toignite a secondary explosive at atmospheric pressure istherefore high [9-11].

Ignition by a laser beam is an external ignition methodwhich offers a number of advantages when compared toother ignition methods. A non-exhaustive list includes: high temporal and spatial precision and accuracy, minimalignition delay, no need for premixing, simultaneousignition of multiple combustion chambers via optical fibercoupling, an increased ignition probability for a widerrange of mixture ratios and initial chamber conditions(from vacuum to high pressure), as well as an electromagneticinterference (EMI) which is well below permissible levels for space flight. Studies comparing laser and electric spark ignition forfuel rich mixtures has shown that laser ignition ensures ahigher ignition probability for lower pressures and this isindependent of the initial chamber pressure [12]. Laser ignition can be performed in a number of differentways, by direct means, where by the laser energy isabsorbed by the propellants directly upon impingementof the laser beam, or indirectly, whereby the laser energyis transmitted from the laser beam to the propellants viaanother medium, such as metal particles.

Due to the potential to increase both the safety and performance of initiation systems, the use of laser radiation to initiate energetic materials remains a topic of interest.Once the fundamentaldetails of the interactions of laser energy and energetic materials are understood, the laser source and delivery hardware can be designed specifically for this purpose.

EXPERIMENTAL

Materials and Samples. Activated carbon was obtained in the Laboratory of Functional Nanomaterials of the Institute of Combustion Problems (Almaty, Kazakhstan). Mechanical treatment (15 min) of ammonium nitrate (purity 99%) powder was carried out in a planetary mill. Ammonium nitrate was used as an oxidizer in the condensed mixture with a diameter of 212-250 µm. Magnesium (Mg) was used as a fuel, and its diameter was 200 µм. The diameter of the metal oxide particles was 30-40 µm, and it acted as a catalyst. Nitrate cellulose was used as a binder. The diameter and length of the compositions were 3 and 10 mm, respectively.

Measurement of Laser Ignition Characteristics. The schematic diagram illustrated in figure 1 shows the set up used for laser ignition of a sample. A fibre-coupled laser diode operating at a wavelength of 974 nm was used as the igniting source, a laser diode controller was used to set pulse width of 300 ms and laser power (up to 40 W with ~6 mW resolution), and an external pulse generator (RS Components 610–629) was used for triggering the laser. The laser beam output was focused with a focusing lens (50 mm diameter and 50 mm focal length) onto the surface of a sample material. The beam diameter incident on the lens was ~50 mm. The spot sizes on sample surfaces varied from 0.7 to 3.5 mm in diame-ters (± 0.05 mm error). A glass block was used for a strand propellant to sit on for ignition. For laser initiation, 30 samples were prepared and burned in with each composite.

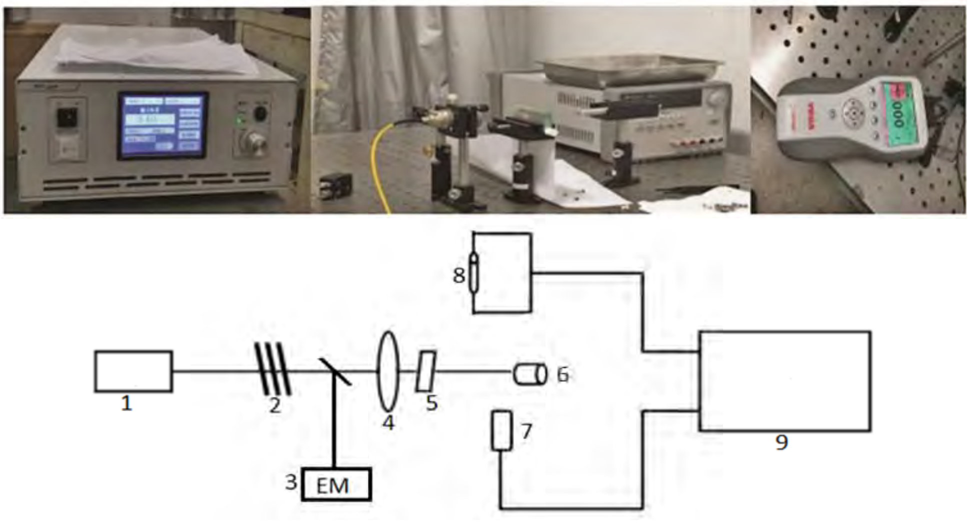

Figure 1 – Experimental set up for laser ignition: 1 – laser diode; 2 – attenuator split; 3 – energy meter; 4 – focusing lens; 5 – glass plate; 6 – sample; 7 – optic detector; 8 – sampling resistance; 9 – data analysis system

Upon correct set up of the equipment, a sample holder containingthe propellant material was placed on a height adjustable stage belowthe focusing lens and the sample surface was positioned at the laserfocus. Following exposure to the laser beam, the sample material wouldbe heated up and ignited with sufficient laser power. The ignition characteristics of the propellant were studied by examining changes in delay time, rise time and burn time across a range of beam widths, laser powers and pulse durations.

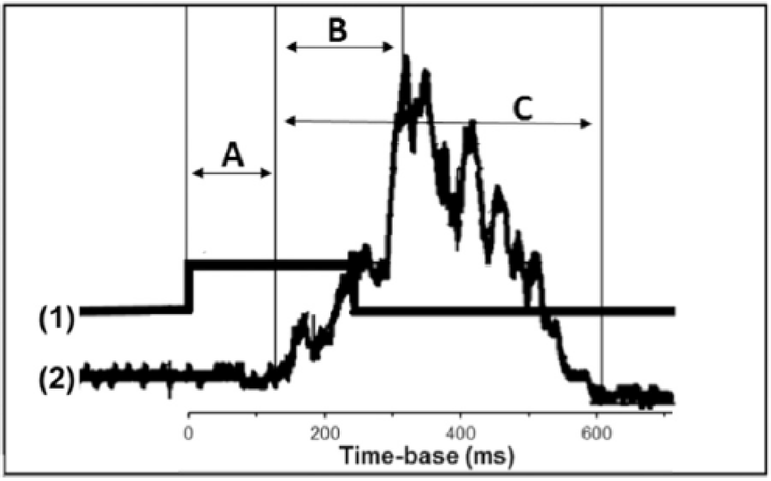

Figure 2 – Oscilloscope traces of (1) laser pulse and (2) the ignited flame with measures: (A) delay time, (B) rise time and (C) burn time

Figure 2 shows graphically the delay time, rise time and burn time measurement definitions. Delay time (A) is taken to be the time between the start of the laser pulse and onset of deflagration of propellant, rise time (B) is taken to be the time between deflagration onset and ignition and burn time (C) is taken to be the time between onset and end of deflagration.

RESULTS AND DISCUSSION

Finding the ignition energy threshold of the propellant was importantas this benchmarked the minimum energy requirements forsubsequent testing. In eachcase, a «Go/No-Go» result was recorded for whether or not the ignitiontook place. Table shows the results of the spent laser energy and ignition delay to initiate for each composition.

According to the results, we can see that the energy spent on laser initiation of the composition decreases (figure 3). As seen for the initiation of the basic composition (AN/Mg) which does not contain activated carbon with metal oxide was spent 25.97 Jof energy. And for the initiation of the composition AN/Mg/C-CuOused 4.35 J of energy, almost four times less energy was spent.

The results of the spent laser energy and ignition delay to initiate for each composition

№	Compositions	Ignition energy, J	Ignition delay, ms
1	AN/Mg	25.97	902
2	AN/Mg/**Carbon**	9.31	810
3	AN/Mg/**C-NiO**	6.88	688
4	AN/Mg/**C-CuO**	4.35	506
*AN – ammonium nitrate.			

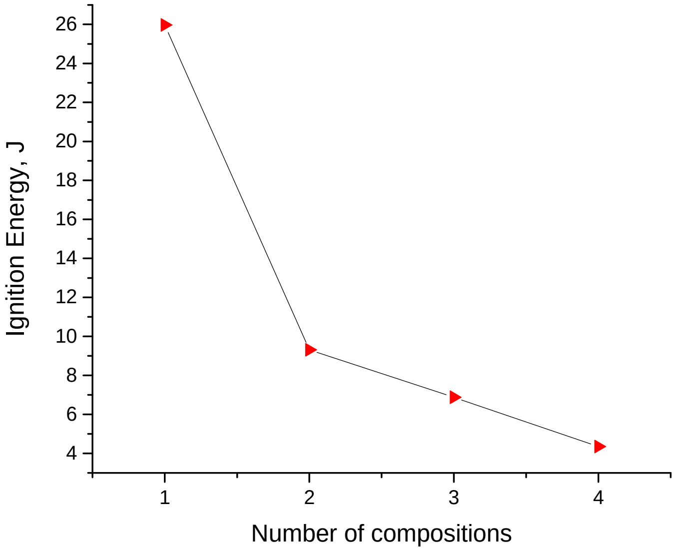

Figure 3 – Ignition energy Dependencies on the compositions

The thermal properties of the energetic material play an important part in addition to the laser energy. This is due to the fact that the activated carbon itself in the form of as a fuel contains a large amount of energy. Metal oxides (CuO/NiO) can be the catalyst for our AN-based propellant system.Ignition by a low-medium laser energy of continuous wave is a complicated process, which includes transfer and dissipation of the heat generated by laser and also the energetic material decomposition in a long-time scale.

The delay time is of particular interest as it can affect both system safety and system response times. Figure 4 presents the dependencies of the ignition delay time on the compositions. As shown, to initiate the compositions with a decrease in energy expended, the delay of the ignition time was also reduced. Ignition delay of basic AN/Mg composition was 902 msand for the AN/Mg/C/CuO composition reduced to 506 ms.It could be said that the composition with activated carbon based on metal oxides reacts quickly to inflammation and is sensitive to initiation.

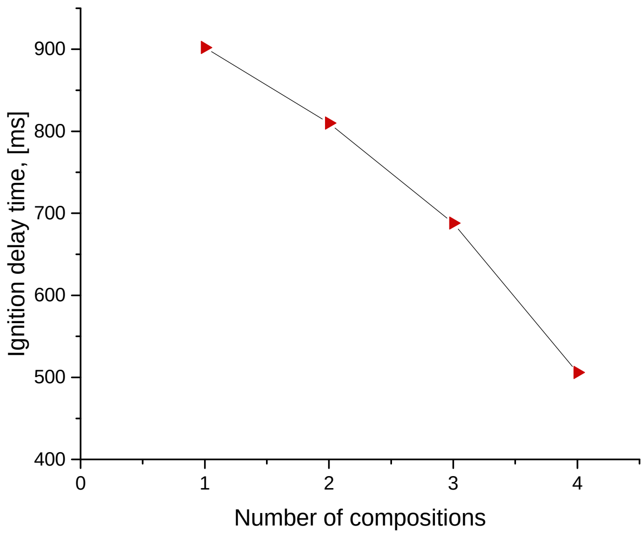

Figure 4 – Dependencies of the ignition delay time on the compositions

Conclusion. This study shows that laser ignition limit for the propellant depends on laser energy and ignition delay and demonstrates that AN/Mg/C/MeO propellant is a good candidate for laser ignition for several reasons. Firstly, the propellant does not require the addition of any optical sensitizers in order to achieve reliable and sustainable ignition, meaning that chemical properties are retained. Secondly, the propellant burned sustainably at a laser energy of ≥4.35 J, providing that ignition delay was 506 ms. The findings of this study support the development of a laser-diode propellant ignitor based on direct ignition of the propellant charge without the need for sensitive pyrotechnics or primary explosives.

REFERENCES

[1] Bowden M.D., Cheeseman M., Knowles S.L., Drake R.C. Laser initiation ofenergetic materials: a historical overview. Proc. SPIE 6662. 2007. P. 208-212.

[2] Fang X., McLuckie W.G. Laser ignitability of insensitive secondary explosive 1,1-diamino-2,2-dinitroethane (FOX-7) // J. Hazard. Mater. 2015. Vol. 285. P. 375-382.

[3] Klapotke M. Laser initiation of tris(carbohydrazide) metal (II) perchlorates andbis(carbohydrazide) diperchlorato-copper (II) // Propellants, Explos., Pyrotech. 2015. Vol. 40. P. 246-252.

[4] Damm D., Maiorov M. Thermal and radiative transport analysis of laser ignition ofenergetic materials // Proc. SPIE. 2010. Vol. 7795. P. 502-512.

[5] Ahmad S.R., Contini A.E., Fang X. Laser ignition of PolyPZ-Q (an opticallysensitised-polyphosphazene) and its formulations with HNS // Proceedings of the43th International Conference of Fraunhofer ICT. Karlsruhe, Germany, 2012.

[6] Abdulazeem M.S., Alhasan A.M., Abdulrahmann S. Initiation of solid explosives bylaser // Int. J. Therm. Sci. 2011. Vol. 50. P. 2117-2121.

[7] Aluker E.D., Krechetov A.G., Mitrofanov A.Y., Nurmukhametov D.R. Laser ignitionof PETN containing light-scattering additives // Tech. Phys. Lett. 2010. Vol. 36. P. 285-287.

[8] Maiorov M., Damm D., Trofimov I., Zeidel V., Sellers R. Reliability assessment of GaAs- and In Pb aseddiode lasers for high-energy single-pulse operation // Proc. SPIE Optical Technologies for Arming, Safing, Fuzing, and Firing. 2009.

[9] Nilsson H., Östmark H. Laser Ignition of Explosives:Raman Spectroscopy of The Ignition Zone // Proceedings of the Ninth Symposium (International) on Detonation, Portland, Oregon, August 27 – September 1, 1989. Vol. 1151.

[10] Östmark H., Bergman H., Ekwall K. LaserPyrolysis of Explosives combined with Mass SpectralStudies of The Ignition Zone // Journal of Analytical andApplied Pyrolysis. 1992. Vol. 24. P. 163.

[11] Östmark H., Ekwall K., Carlsson M., Bergman H., Pettersson A. Laser Ignition of Explosives: A LIF Study of The RDX Ignition Zone // Proceedings of the Tenth Symposium (International) on Detonation, Boston Massachusettes, July 12–16, 1993. P. 555.

[12] McIntyre D. A Laser Spark Plug Ignition System fora Stationary Lean-Burn Natural Gas Reciprocating Engine. Ph.D. thesis. West Virginia University, 2007.

Резюме

Ж. К. Елемесова, З. А. Мансуров, Б. Т. Лесбаев, Р. Шен

МЕТАЛ ОКСИД НЕГІЗІНДЕГІ КӨМІРТЕКҚҰРАМДЫ ЭНЕРГЕТИКАЛЫҚ КОМПОЗИЦИЯЛЫҚ ПРОПЕЛЛАНТТЫҢ ЛАЗЕРЛІК ТҰТАНУЫ

Тікелей тұтануды тиімді ету мақсатында метал оксиді негізіндегі құрамында көміртек бар энергетикалық композициялық пропеллантқа диод лазерін қолдану арқылы тәжірибелік зерттеу жүргізілді. Отын үлгілеріне 974 нм-лік жақын инфрақызыл диодтың лазері пайдаланылды. Лазерлік сәуле параметрлері, соның ішінде лазерлік энергия, сәулесінің ені және серпін ені, әртүрлі конфигурацияда орналасқан кідірту уақытын көтеру мен отынның жағу уақытында тұтану сипаттамаларына әсерін анықтау үшін зерттелді. Алынған нәтижелер бойынша сәуленің кішірек ені, импульстің үлкен ені және қысқа лазерлік энергиясы қысқа тұтанудың кешігу уақытына және толық жану уақытына әкелетінін көрсетті, алайда лазерлік энергияның көбеюі тұтанудың уақытын азайтпайды. Зерттелінген отын лазерлік тұтануға оң әсер етті және ол лазерлік отын тұтатқыштарын игеруде жүргізіліп жатқан зерттеулерді қолдайды.

Түйін сөздер: лазерлік тұтану, тұтану кешігуі, жану, энергетикалық материалдар, белсендірілген көмір, металл оксиді.

Резюме

Ж. К. Елемесова, З. А. Мансуров, Б. Т. Лесбаев, Р. Шен

ЛАЗЕРНОЕ ИНИЦИИРОВАНИЕ
УГЛЕРОДСОДЕРЖАЩИХ ЭНЕРГЕТИЧЕСКИХ КОМПОЗИЦИЙ
НА ОСНОВЕ МЕТАЛОКСИДНОГО ПРОПЕЛЛАНТА

Экспериментальное исследование было проведено для изучения лазерного воспламенения с использованием диодного лазера для углеродсодержащих энергетических композиций на основе металлоксидного пропелланта с целью разработки более надежных и более зеленых лазерных воспламенителей для прямого инициирования пропелланта. Образцы топлива зажигались с использованием 974 нм ближнего инфракрасного диодного лазера. Параметры лазерного луча, включая энергию лазера, ширину луча и ширину импульса, были исследованы для определения их влияния на характеристики зажигания с точки зрения времени задержки, времени нарастания и времени горения топлива, которое было расположено в нескольких различных конфигурациях. Результаты показали, что меньшая ширина луча, большая ширина импульса и более короткая энергия лазера приводят к более коротким временам задержки зажигания и полному времени горения, однако увеличение количества лазерной энергии, передаваемой материалу, не приводит к значительному сокращению времени задержкиили общее время записи. Испытанный пропеллант хорошо реагировал на лазерное воспламенение, расширение, которое поддерживает продолжающиеся исследования в разработке лазерных воспламенителей топлива.

Ключевые слова: лазерное инициирование, задержка зажигания, горение, энергетические материалы, активированный уголь, оксид металла.