DISPERSION OF CONDENSED COMBUSTION PRODUCTS OF METALLIZED ENERGY-INTENSIVE MATERIALS IN THE FIELD OF MULTIDIRECTIONAL INERTIAL LOADS

V. V. Mironov, M. A. Mishchenko, and S. A. Degtyaryov

JSC "Keldysh Research Center," 8 Onezhskaya Str., Moscow 125438, Russian Federation

Abstract: An experimental study of the effect of overloads of varying magnitude and direction on the dispersed composition of condensed combustion products (CCP) of metallized mixed energy-intensive materials was performed using a centrifugal stand. Mass integral distribution functions, average mass sizes, and fractions of particle content in combustion products were established. The elemental composition of samples was determined. A nonmonotonic dependence of the mass-average size of particles on the overload was revealed for tearing overloads: an increase in the mass-average size of particles is observed with an increase in overloads from $3.3g$ to $11.1g$ and a decrease with an increase from $11.1g$ to $30g$. Pressing overloads lead to the formation of a nonentrained liquid layer of aluminum and its oxide on the burning surface. When analyzing the obtained experimental data, the results of modeling the flow and interaction of CCP particles in sample capsules were taken into account. The calculation results provide additional information on the flow structure inside the region and the mechanisms of interaction of CCP particles with each other and with the walls of the sample capsule.

Keywords: condensed combustion products; energy-intensive materials; overloads; centrifuge; agglomeration of aluminum; functions of distribution; mass-average sizes

DOI: 10.30826/CE25180410 **EDN:** PYMERM

Figure Captions

Figure 1 Schematic of the experimental centrifuge: *1* — platform; *2* — selecting capsules; *3* — electric motor with gearbox; *4* — drive shaft; and *5* — onboard data collection and recording system

Figure 2 Reproducible overload values

Figure 3 Mass-average particle size of CCP

Figure 4 Mass fraction of particles z in combustion products

Figure 5 The fraction of CCP mass remained on the burning surface

Figure 6 Cumulative particle size distribution functions for tearing ($g > 1$) and pressing ($g < -1$) overloads: *1* — 27,52g; *2* — 22,04g; *3* — 16,57g; *4* — 11,1g; *5* — 8,32g; *6* — 6,67g; *7* — 5,01g; *8* — 3,36g; *9* — 1g; *10* — −29,5g; *11* — −24g; *12* — −18,6g; *13* — −8,93g; *14* — −7,27g; *15* — −5,62g; *16* — −3,96g; and *17* — −1g

Figure 7 Photographs of CCP microstructure: (*a*) pressing overloads; and (*b*) tearing overloads

Figure 8 Mass-average CCP particle size: black color — experimental results; and grey color — calculation

Figure 9 Comparison of the calculated and experimental data for the fraction of CCP mass remained on the burning surface: black color — experimental results; and grey color — calculation

Table Caption

Elemental composition of two CCP samples

References

1. Alemasov, V. E., A. F. Dregalin, and A. P. Tishin. 1980. *Teoriya raketnykh dvegateley* [Theory of rocket engines]. Moscow: Mashinostroenie. 535 p.
2. Sternin, L. E., B. N. Maslov, and A. A. Shraiber. 1980. *Dvykhfaznye mono- i polidispersnye techeniya gaza s chastitsami* [Two-phase mono- and polydisperse gas flows with particles]. Moscow: Mashinostroenie. 172 p.
3. Babuk, V. A., and N. L. Budny. 2017. Modelirovanie evolyutsii vysokodispersnogo oksida v sostave potoka produktov sgoraniya alyuminizirovannogo tverdogo topliva [Modeling of smoke oxide particles evolution in flow of combustion products of aluminized solid propellant]. *Khimicheskaya fizika i mezoskopiya* [Chemical Physics and Mesoscopy] 19:5–19.
4. Pokhil, P. F., A. F. Belyaev, Yu. V. Frolov, V. S. Logachev, and A. I. Korotkov. 1972. *Gorenie poroshkoobraznykh metallov v aktivnykh sredakh* [Combustion of powdered metals in active environments]. Moscow: Nauka. 294 p.
5. Assovsky, I. G. 2005. *Fizika goreniya i vnutrennyaya ballistika* [Combustion physics and interior ballistics]. Moscow: Nauka. 357 p.

6. Gremyachkin, V. M. 2015. *Geterogennoe gorenie chasitits tverdykh topliv* [Heterogeneous combustion of solid fuel particles]. Moscow: Bauman Moscow State Technical University Publishing House. 230 p.
7. Margolin, A. D., and V. G. Krupkin. 1978. Effect of overloads on the combustion rate of compositions containing up to 80% aluminum. *Combust. Explo. Shock Waves* 14(3):42–49.
8. Poryazov, V. A., D. A. Kraynov, and A. A. Blokhina. 2022. Gorenie zaryada metallizirovannogo smesevogo tverdogo topliva s ploskim kanalom v pole massovykh sil [Combustion of a charge of metallized composite solid propellant with a flat channel in a mass force field]. *Tomsk State University J. Mathematics and Mechanics* 75:113–121. doi: 10.17223/19988621/75/10.
9. Korotkikh, A. G., I. V. Sorokin, D. V. Teplov, and V. V. Arkhipov. 2023. Combustion characteristics of high-energy material containing dispersed aluminum, boron, and aluminum borides. *Combust. Explo. Shock Waves* 59(4):440–446. doi: 10.1134/s0010508223040068. EDN: QCWSHO.
10. Babuk, V. A., V. A. Vasiliev, and A. N. Potekhin. 2009. Experimental investigation of agglomeration during combustion of aluminized solid propellants in an acceleration field. *Combust. Explo. Shock Waves* 45(1):32–39. doi: 10.1007/s10573-009-0005-9. EDN: LLSVML.
11. Rashkovsky, S. A. 2007. Effect of acceleration on agglomeration of aluminum particles during combustion of composite solid propellants. *Combust. Explo. Shock Waves* 43(6):654–663. doi: 10.1007/s10573-007-0088-0. EDN: LKEKFT.
12. Mironov, V. V., M. A. Mishchenko, D. V, Khakimov, and S. A. Degtyarev. 2024. Experimental study of the dispersion of condensed combustion products of metallized energy-intensive materials in the field of multidirectional inertial forces. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 17(2):92–98. doi: 10.30826/CE24170209.
13. Borisov, D. M., S. A. Degtyarev, M. A. Mishchenko, I. R. Zharov, and N. D. Seliverstov. 2021. Methodology of experimental study of the composition and properties of condensed combustion products of solid fuels. *Boepripasy* [Ammunition] 2:40–46.

Received April 9, 2025
After revision August 19, 2025
Accepted August 25, 2025

Contributor

Mironov Vadim V. (b. 1958) — Doctor of Science in technology, professor, head of department, JSC "Keldysh Research Center," 8 Onezhskaya Str., Moscow 125438, Russian Federation; mironov@kerc.msk.ru

Mishchenko Mikhail A. (b. 1992) — Candidate of Science in technology, senior research scientist, JSC "Keldysh Research Center," 8 Onezhskaya Str., Moscow 125438, Russian Federation; mishchenko@kerc.msk.ru

Degtyaryov Sergey A. (b. 1985) — Candidate of Science in technology, head of laboratory, JSC "Keldysh Research Center," 8 Onezhskaya Str., Moscow 125438, Russian Federation; degtyarev@kerc.msk.ru