NUMERICAL STUDY OF GUN POWDER DEFLAGRATION USING BAER–NUNZIATO MODEL

P. A. Chuprov[1,2], Ya. E. Poroshyna[2], and P. S. Utkin[2]

[1]Moscow Institute of Physics and Technology, 9 Institutskiy Per., Dolgoprudny, Moscow Region 141701, Russian Federation

[2]Institute for Computer Aided Design of the Russian Academy of Sciences, 19/18 Brestskaya 2nd Str., Moscow 123056, Russian Federation

Abstract: The work addresses the clarification of the hyperbolic Baer–Nunziato model usage for the numerical simulation of the deflagration wave propagation in the black powder charge. Although the Baer–Nunziato equations have been used for the simulations of combustion and detonation of the heterogeneous explosives for a long time, there are only few works in which this model is used for the gun powders. The model takes into account the compaction effects of the gun powder condensed phase. The numerical algorithm is based on the Harten – Lax – van Leer method; an important element of the algorithm is the pressure relaxation procedure which provides the local equilibrium of the interfacial boundaries taking into account the intergranular stresses. The statement of the problem corresponds to the full-scale experiment of B. S. Ermolaev with coauthors. The correct wave pattern is obtained in the simulations, namely, the leading compaction wave, the combustion wave that follows the previous one, and the waves reflected from the side walls of the channel. The explanation of the pressure curves at the transducers is given from the analysis of the realized flow field. The comparison of the obtained pressure curves at the transducers and spatial distributions of the flow parameters with the results of B. S. Ermolaev with coauthors is carried out.

Keywords: numerical simulation; Baer–Nunziato equations; gun powder; internal ballistics; compaction; Harten – Lax – van Leer numerical method

DOI: 10.30826/CE20130309

Figure Captions

Figure 1 Comparison of pressure sensors readings in the authors' simulation (*1*) and in [13] (*2*)

Figure 2 Predicted spatial distributions of $\overline{\alpha}$, p, $\overline{p}$, and $\overline{T}$ at the time moment 0.4 ms that explain the pressure curves before the compaction wave reflection from the right wall of the channel

Figure 3 Predicted spatial distributions of $\overline{\alpha}$, p, and ν at the time moment 0.8 ms that explain the pressure curves after the compaction wave reflection from the right wall of the channel

Figure 4 Comparison of the spatial distributions of the gas pressure, porosity, and velocities of the phases in the authors' simulation (*1*) and in [13] (*2*). Time moment 0.6 ms

Figure 5 Approximate analytical model of the heating of the powder element

Table Captions

Table 1 Initial distributions of the temperatures of gas and solid phases

Table 2 Physical and chemical parameters of black powder and its combustion products

Table 3 Combustion and compaction wave velocities

Acknowledgments

The work was carried out within the State task of the Institute for Computer Aided Design of the Russian Academy of Sciences.

References

1. Khomenko, Y. P., A. N. Ischenko, and V. Z. Kasimov. 1999. *Matematicheskoe modelirovanie vnutriballisticheskikh protsessov v stvol'nykh sistemakh* [Mathematical modeling of interior ballistic processes in barrel systems]. Novosibirsk: Publishing House of SB RAS. 256 p.
2. Rusjak, I. G., and V. M. Ushakov. 2001. *Vnutrikamernye geterogennye protsessy v stvol'nykh sistemakh* [Heterogeneous in-chamber processes in stock systems]. Ekaterinburg: Publishing House of UB RAS. 259 p.
3. Koo, K. K., J. H. Kuo, T. R. Davis, and G. R. Coates. 1976. Transient combustion in mobile gas-permeable propellants. *Acta Astronaut.* 3:573–559. doi: 10.1016/0094-5765(76)90163-6.
4. Gallouet, T., P. Helluy, J.-M. Herard, and J. Nussbaum. 2010. Hyperbolic relaxation models for granular flows. *ESAIM Math. Model. Numer.* 44:371–400. doi: 10.1051/m2an/2010006.
5. Akhatov, I. Sh., and P. B. Vainshtein. 1983. Nonstationary combustion regimes in porous powders. *Combust. Explo. Shock Waves* 19:297–304. doi: 10.1007/BF00782853.
6. Nigmatulin, R. I. 1990. *Dynamics of multiphase media*. New York, NY: Hemisphere Publ. Corp. 507 p.
7. Baer, M. R., and J. W. Nunziato. 1986. A two-phase mixture theory for the deflagration-to-detonation transition in reactive granular materials. *Int. J. Multiphas. Flow* 21(26):861–889. doi: 10.1016/0301-9322(86)90033-9.
8. Sen, O., N. K. Rai, A. S. Diggs, D. B. Hardin, and H. S. Udaykumar. 2018. Multi-scale shock-to-detonation simulation of pressed energetic material: A meso-informed ignition and growth model. *J. Appl. Phys.* 124:085110. doi: 10.1063/1.5046185.
9. Longuet, B., P. D. Pieta, P. Franco, G. Legeret, A. Papy, D. Boisson, C. Reynaud, P. Millet, E. Taiana, and A. Carrere. 2005. MOBIDIC-NG: A 1D/2D CFD code suitable for interior ballistics and vulnerability modelling. *22nd Symposium (International) on Ballistics Proceedings*. Vancouver, Canada. 362–371.
10. Nissbaum, J., P. Helluy, J.-M. Herard, and B. Baschung. 2012. Multi-dimensional two-phase flow modeling applied to interior ballistics. *J. Appl. Mech.* 78:051016. doi: 10.1115/1.4004293.
11. Ermolaev, B. S., A. A. Sulimov, V. A. Foteenkov, V. E. Khrapovskii, A. I. Korotkov, and A. A. Borisov. 1980. Nature and laws governing quasi-steady-state pulsed convective combustion. *Combust. Explo. Shock Waves* 16:266–274. doi: 10.1007/BF00742126.
12. Foteenkov, V. A., A. I. Korotkov, B. S. Ermolaev, and A. A. Sulimov. 1982. Propagation of convective combustion in poured-density explosives. *Combust. Explo. Shock Waves* 18(2):250–252. doi:10.1007/BF00789627.
13. Ermolaev, B. S., A. A. Belyaev, S. B. Viktorov, K. A. Sleptsov, and S. Yu. Zharikova. 2010. Nonideal regimes of deflagration and detonation of black powder. *Russ. J. Phys. Chem. B* 4:428–439. doi: 10.1134/S1990793110030103.
14. Saurel, R., and R. Abrall. 1999. A multiphase Godunov method for compressible multifluid and multiphase flows. *J. Comput. Phys.* 150:425–467. doi: 10.1006/jcph.1999.6187.
15. Bdzil, J. B., R. Menikoff, S. F. Son, A. K. Kapila, and D. S. Stewart. 1999. Two-phase modeling of deflagration-to-detonation transition in granular materials: A critical examination of modeling issues. *Phys. Fluids* 11(2):378–402. doi: 10.1063/1.869887.
16. Schwendeman, D. W., C. W. Wahle, and A. K. Kapila. 2008. A study of detonation evolution and structure for a model of compressible two-phase reactive flow. *Combust. Theor. Model.* 12(1):159–204. doi: 10.1080/13647830701564538.
17. Utkin, P. S. 2017. Mathematical modeling of the interaction of a shock wave with a dense cloud of particles within the framework of the two-fluid approach. *Russ. J. Phys. Chem. B* 11(6):963–973. doi: 10.1134/S1990793117050141.
18. Utkin, P. 2019. Numerical simulation of shock wave – dense particles cloud interaction using Godunov solver for Baer–Nunziato equations. *Int. J. Numer. Method. H.* 29(9):3225–3241. doi: 10.1108/HFF-10-2018-0587.
19. Poroshyna, Ya., and P. S. Utkin. 2020. Chislennoe modelirovanie vzaimodeystviya normal'no padayushchey udarnoy volny so sloem chastits v ramkakh uravneniy Baera–Nuntsiato [Numerical simulation of interaction of the normally incident shock wave with a layer of particles using Baer–Nunziato system of equations]. *Goren.Vzryv (Mosk.) —Combustion and Explosion* 13(1):95–104. doi: 10.30826/CE20130109.
20. Saurel, R., N. Favrie, F. Petitpas, M.-H. Lallemand, and S. L. Gavrilyuk. 2010. Modelling dynamic and irreversible powder compaction. *J. Fluid Mech.* 664:348–396. doi: 10.1017/S0022112010003794.
21. Serebryakov, M. E. 1962. *Vnutrennyaya ballistika stvol'nykh sistem i porokhovykh raket* [Internal ballistics of barrel systems and powder rockets]. Moscow: Oborongiz. 703 p.
22. Le Metayer, O., and R. Saurel. 2016. The Noble–Abel stiffened gas equation of state. *Phys. Fluids* 28:046102. doi: 10.1063/1.4945981.
23. Radulescu, M. I. 2019. On the Noble–Abel stiffened-gas equation of state. *Phys. Fluids* 31:111702. doi: 10.1063/1.5129139.
24. Frolov, S. M., and V. A. Smetanyuk. 2006. Heat and mass transfer of droplet with gas flow. *Russ. J. Phys. Chem. B* 25(4):42–54.
25. Utkin, P. S., and Ya. E. Poroshyna. 2019. Chislennoe modelirovanie geterogennoy detonatsii s ispol'zovaniem metoda HLL dlya uravneniy Baera–Nuntsiato [Numerical simulation of heterogeneous detonation using HLL method for Baer–Nunziato equations]. *Goren. Vzryv (Mosk.) — Combustion and Explosion* 12(1):84–89. doi: 10.30826/CE19120110.
26. Abgrall, R. 1996. How to prevent pressure oscillations in multicomponent flow calculations: A quasi conservative

approach. *J. Comput. Phys.* 125:150–160. doi: 10.10006/jcph.1996.0085.

27. Poroshyna, Y., and P. Utkin. 2019. Pressure relaxation procedure with compaction for the problems of shock wave – particles beds interaction. *32nd Symposium (International) on Shock Waves Proceedings*. Singapore. OR-14-0254:1649–1656. doi: 10.3850/978-981-11-2730-4_0254-cd.
28. Semenov, I. V., P. S. Utkin, I. F. Akhmedyanov, and I. S. Menshov. 2011. Primenenie mnogoprotsessornoy vychislitel'noy tekhniki dlya resheniya zadach vnutrenney ballistiki [Application of high performance computing to the solution of interior ballistics problems]. *Vychislitel'nye metody i programmirovanie* [Numerical Methods and Programming] 12(1):183–193.
29. Shilling, N. A. 1940. *Kurs dymnykh porokhov* [The course of black powders]. Moscow: GIOP. 155 p.
30. Khmel', T. A., and A. V. Fedorov. 2014. Modeling of propagation of shock and detonation waves in dusty media with allowance for particle collisions. *Combust. Explo. Shock Waves* 50(5):547–555. doi: 10.1134/S0010508214050104.
31. Menshov, I. S., M. Y. Nemtsev, and I. V. Semenov. 2019. Numerical modeling of wave processes accompanying combustion of inhomogeneously distributed composite propellant. *Comp. Math. Math. Phys.* 59(9):1591–1604. doi: 10.1134/S0965542519090148.
32. Ozisik Necati, M. 1993. *Heat conduction*. 2nd ed. John Wiley & Sons. 692 p.
33. Nusca, M. J., and P. J. Controy. 2001. Multiphase CFD simulations of solid propellant combustion in gun systems. *DoD High Performance Computing Modernization Program Users Group Conference Proceedings*. Biloxi, MS.

Received August 12, 2020

Contributors

Chuprov Petr Anatolievich (b. 1996) — first-year PhD student, Moscow Institute of Physics and Technology, 9 Institutskiy Per., Dolgoprudny, Moscow Region 141701, Russian Federation; research assistant, Institute for Computer Aided Design of the Russian Academy of Sciences, 19/18 Brestskaya 2nd Str., Moscow 123056, Russian Federation; petchu@mail.ru

Poroshyna Yaroslava Eduardovna (b. 1996) — junior research scientist, Institute for Computer Aided Design of the Russian Academy of Sciences, 19/18 Brestskaya 2nd Str., Moscow 123056, Russian Federation; poroshina@phystech.edu

Utkin Pavel S. (1985) — Candidate of Science in physics and mathematics, senior research scientist, Institute for Computer Aided Design of the Russian Academy of Sciences, 19/18 Brestskaya 2nd Str., Moscow 123056, Russian Federation; pavel_utk@mail.ru