HiSST: International Conference on
High-Speed Vehicle Science Technology

26–29 November 2018, Moscow, Russia

Study of Detonation Waves by Means of Mathematical Modeling

V.Levin[1,2,3], I.Manuylovich[1,2], V.Markov[1,2,4]

Abstract

Keywords: three-dimensional nonstationary flow, rotating detonation, numerical study

1. Introduction

According to experimental data and the results of theoretical studies, the existence of self-sustained waves of gas detonation is associated with nonstationary processes and the formation of periodic flow structures [1-3]. Numerical studies of the initiation of detonation in the one-dimensional approximation revealed a nonstationary wave structure of detonation. According to calculations, such a wave is always nonstationary, and the wave velocity and parameters on its leading edge vary periodically under the influence of shock waves formed in the induction zone ahead of the accelerating front of flame [4-7]. It turned out that an autooscillatory process develops only when the value of the initiation energy exceeds a certain critical value. Otherwise, the detonation wave decays, decaying into a shock wave and a wave of slow combustion. The values of the critical energy at initiation of detonation were determined various external sources of energy [8-11], as well as the possibility of initiation of detonation as a result of the collapse of a spherical or cylindrical region with reduced pressure without additional energy supply from outside [12-14]. According to the results of calculations of the development of a local perturbation of a plane wave, in the two-dimensional approximation, instead of longitudinal one-dimensional waves, transverse waves are formed andthe cellular structure observed in the experiments [15]. The two-dimensional spin model used by many researchers was formulated, and the structure of a two-headed spin detonation wave was calculated [7]. Wave processes were studied during detonation both in a hydrogen-air mixture at rest and in a supersonic flow [16-19]. Special attention was paid in the last decade to problems of initiation and stabilization of detonation in limited volumes of combustion chambers of power plants that realize high-speed combustion of fuel. The use of high-performance computer technology made it possible to investigate multidimensional flows during the initiation of detonation due to the energy of the motion of the combustible mixture and in its interaction with moving boundaries [20-24]. In this case, previously unknown modes of propagation of waves of chemical reactions, including galloping layered detonation, were detected. A detailed numerical study of the formation and stability of three-dimensional spin detonation is carried out [25]. The most promising from the point of view of practice is a rotating detonation. In this connection, it draws special attention to both experimentalists and theoreticians [26].Currently, the development and creation of power plants are associated with the use of methods of mathematical modeling using a multiprocessor computer techniques. This article presents the results of numerical studies of the combustion of propane-air mixture in a rotating detonation wave in a device of a special design. For calculations, the supercomputer of the Lomonosov Moscow State University was used [27], where earlier three-dimensional non-stationary reacting flows were calculated on grids with billions of computed cells. Similar calculations of rotating detonation were performed for the first time in Russia. Similar problems are dealt with in the Institute of Hydrodynamics. M.A. Lavrent'ev, Siberian Branch of the Russian Academy of Sciences, where a series of experimental and theoretical studies devoted to combustion chambers with rotating detonation was carried out.

[1] *Institute of Mechanics, M.V. Lomonosov Moscow State University, 119192, Moscow, Russia, levin@imec.msu.ru*
[2] *Central Aero Hydrodynamic Institute, 140180, Zhukovsky, Russia, info@tsagi.ru*
[3] *Institute for Automatics and Control Processes FEB RAS, 690041, Vladivostok, Russia, user@iacp.dvo.ru*
[4] *Steklov Mathematical Institute of Russian Academy of Sciences, 119991, Moscow, Russia, markov@mi.ras.ru*

2. Detonation in the annular gap

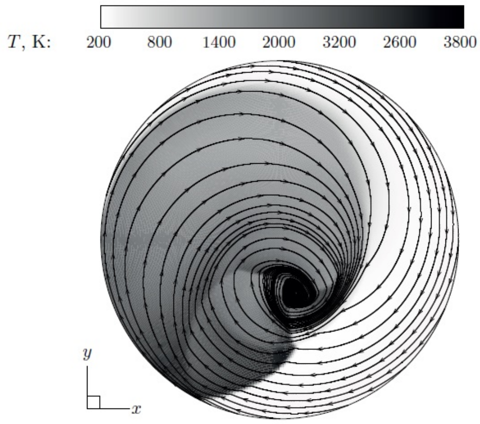
The problem of a three-dimensional nonstationary flow with a rotating detonation wave arising in the annular gap of an axisymmetric device between two parallel planes perpendicular to its axis of symmetry is investigated. It is assumed that a homogeneous combustible propane-air mixture, resting in a reservoir with predetermined braking parameters, enters the annular gap through its outer cylindrical surface towards the axis of symmetry and its parameters are determined by the pressure in the reservoir and the static pressure in the gap. The detonation products flow out of the gap into space, bounded on one side by an impenetrable wall-the continuation of the side of the gap. Through the hole in the other side of the gap and the conical exit section with the angle of half-solution 45, the gas flows out of the device into the outer space. The model of detonation initiation by the energy supply is formulated, in which the direction of rotation of the detonation wave is determined by the location of the energy release zone of the initiator relative to the solid wall located in the plane passing through the axis of symmetry. After a certain time, this solid wall disappears (burns). Nonstationary shock-wave structures arising in the process of formation of a stationary rotating detonation are obtained and analyzed. To describe gasdynamic three-dimensional unsteady flows, the Euler equations system for an ideal multicomponent reacting mixture in a fixed Cartesian coordinate system is used. The detonation of a stoichiometric propane-air mixture in the framework of a one-stage kinetics with one irreversible reaction is considered [28]. The study is carried out by the modified method of S.K. Godunov [29] of the first order of accuracy with respect to space and time. The method is implemented in the original software package designed to solve a wide range of one-dimensional, two-dimensional and three-dimensional problems of non-stationary dynamics of gaseous combustible mixtures. The software complex has a graphical interface with visualization functions. The computational algorithm is parallelized on the basis of MPI and allows the calculation of tasks with the number of calculated cells of several billion. In this paper, we present the results obtained on a supercomputer of the Lomonosov Moscow State University with calculated grids containing 0.1 to 10 billion cells.

A series of calculations was carried out, which made it possible to obtain optimal values for the parameters of the initiators of rotating detonation. It is established that a rotating detonation wave is formed in the chamber, the direction of rotation of which is determined by the location of the energy release zone of the initiator relative to the solid wall, In the plane passing through the axis of symmetry. After a certain time, this solid wall disappears (burns). Nonstationary shock-wave structures arising in the process of formation of a stationary rotating detonation are obtained and analyzed.

To describe gasdynamic three-dimensional unsteady flows, the Euler equations system for an ideal multicomponent reacting mixture in a fixed Cartesian coordinate system is used. The detonation of a stoichiometric propane-air mixture in the framework of a one-stage kinetics with one irreversible reaction is considered [28]. The study is carried out by the modified method of S.K. Godunov [29] of the first order of accuracy with respect to space and time. The method is implemented in the original software package designed to solve a wide range of one-dimensional, two-dimensional and three-dimensional problems of non-stationary dynamics of gaseous combustible mixtures. The software complex has a graphical interface with visualization functions. The computational algorithm is parallelized on the basis of MPI and allows the calculation of tasks with the number of calculated cells of several billion. In this paper, we present the results obtained on a supercomputer of the Lomonosov Moscow State University with calculated grids containing 0.1 to 10 billion cells.

A series of calculations was carried out, which made it possible to obtain optimal values for the parameters of the initiators of rotating detonation. It is established that a rotating detonation wave is formed in the chamber, the direction of rotation of which is determined by the location of the energy release zone of the initiator relative to the solid wall, In the plane passing through the axis of symmetry. After a certain time, this solid wall disappears (burns). Nonstationary shock-wave structures arising in the process of formation of a stationary rotating detonation are obtained and analyzed.

Below, the figure shows the temperature field for steady-state rotation of the detonation. On it are superimposed streamlines constructed in a coordinate system rotating with the wave. In this figure, a vortex zone is visible and the current lines on shock waves are refracted. All streamlines emerge from the boundary circle at the same angle, determined by the ratio of the leak-in rate and the linear velocity during the rotation of the detonation. In the restricted zone, there is no inflow behind the detonation wave and the streamlines are parallel to the boundary circle. In the figure, the contact surface between the shock waves b and e is visible. It separates a dark zone with an elevated temperature and a dense arrangement of streamlines and a light zone of a heated mixture in which the streamlines are more sparse. It is clearly seen that the contact surface in question coincides with one of the spiral streamlines ending at the center of the vortex zone.



Temperature field with current lines for steady-state rotation of detonation. Current Linesare constructed in a coordinate system rotating with the wave.

3. Acknowledgments

This research has been supported by the Ministry of Education and Science of the Russian Federation (contract 14.G39.31.0001 on 13.02.2017). Influence of the addition of fine inert dust particles into gas mixture on detonation stabilization has been studied with the assistance of the Russian Foundation for Basic Research (projects 16-29-01092, 18-01-00883). The research is carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University [4].

References

1. Korobeinikov V.P., Levin V.A., Markov V.V., Chernyi G.G. Propagation of blast waves in a combustible gas // Astronaut. acta. 1972. V. 17, N 5–6. P. 529–537.
2. Митрофанов В.В., Солоухин Р.И. О дифракции многофронтовой детонационной волны // ДАН СССР. 1964. Т. 159, №5. С. 1003–1006.
3. Солоухин Р.И. Структура многофронтовой детонационной волны в газе // Физика горения и взрыва. 1965. Т. 1, №2. С. 35–42.
4. Korobeinikov V.P., Markov V.V. On propagation of combustion and detonation // Arch. proces´ow spalania. 1977. V. 8, N 1. P. 101–118.
5. Левин В.А., Марков В.В., Осинкин С.Ф. Влияние воздушной прослойки на инициирование взрывом детонации в водородовоздушной смеси // Тр. МИАН. 1998. Т. 223. С. 136–143.
6. Левин В.А., Марков В.В., Журавская Т.А. Прямое инициирование детонации в водородовоздушной смеси сходящейся ударной волной // Хим. физика. 2001. Т. 20, №5. С. 26–30.
7. Седов Л.И., Коробейников В.П., Марков В.В. Теория распространения взрывных волн // Тр. МИАН. 1986. Т. 175. С. 178–216.
8. Левин В.А., Марков В.В., Осинкин С.Ф. Моделирование инициирования детонации в горючей смеси газов электрическим разрядом // Хим. физика. 1984. Т. 3, №4. С. 611–614.
9. Левин В.А., Марков В.В., Осинкин С.Ф. Инициирование детонации в водородовоздушной смеси взрывом сферического заряда ТНТ // Физика горения и взрыва. 1995. Т. 31, №2. С. 91–95.
10. Левин В.А., Марков В.В., Осинкин С.Ф. Восстановление детонации с помощью разрушающейся оболочки // ДАН. 1997. Т. 352, №1. С. 48–50.
11. Левин В.А., Марков В.В., Осинкин С.Ф. Влияние воздушной прослойки на инициирование взрывом детонации в водородовоздушной смеси // Тр. МИАН. 1998. Т. 223. С. 136–143.

12. Левин В.А., Марков В.В., Осинкин С.Ф.,Журавская Т.А. Определение критических условий инициирования детонации в ограниченном объеме сходящейся к центру ударной волной // Физика горения и взрыва.
2002. Т. 38, №6. С. 96–102.
13. Левин В.А., Марков В.В., Журавская Т.А. Прямое инициирование детонации в водородовоздушной смеси сходящейся ударной волной // Хим. физика. 2001. Т. 20, №5. С. 26–30.
14. Журавская Т.А., Левин В.А., Марков В.В., Осинкин С.Ф. Влияние разрушающейся оболочки на формирование детонации в ограниченном объеме сходящейся ударной волной // Хим. физика. 2003. Т. 22, №8.
С. 34–37.
15. Марков В.В. Численное моделирование образования многофронтовой структуры детонационной волны // ДАН СССР. 1981. Т. 258, №2. С. 314–317.
16. Левин В.А., Марков В.В., Журавская Т.А., Осинкин С.Ф. Нелинейные волновые процессы при инициировании и распространении газовой детонации // Тр. МИАН. 2005. Т. 251. С. 200–214.
17. Левин В.А., Марков В.В., Журавская Т.А., Осинкин С.Ф. Определение критических условий распространения волн детонации в каналах сложной формы // Современные проблемы исследования быстропротекающих процессов и явлений катастрофического характера: К 75-летию В.П. Коробейникова / Под ред. О.М. Белоцерковского. М.: Наука, 2007. С. 75–88.
18. Levin V.A., Markov V.V., Zhuravskaya T.A., Osinkin S.F. Initiation, propagation and stabilization of detonation in the supersonic gas flow // Proc. Seventh Int. Symp. on Hazards, Prevention, and Migration of Industrial Explosions (ISHPMIE), St. Petersburg, July 7–11, 2008. Moscow: Torus Press, 2008. V. 2. P. 110–118.
19. Levin V.A., Markov V.V., Zhuravskaya T.A., Osinkin S.F. Influence of obstacles on detonation wave propagation // Deflagrative and detonative combustion / Ed. by G. Roy, S. Frolov. Moscow: Torus Press, 2010. P. 221–228.
20. Левин В.А., Мануйлович И.С., Марков В.В. Новые эффекты слоистой газовой детонации // ДАН. 2010. Т. 430, №2. С. 185–188.
21. Левин В.А., Мануйлович И.С., Марков В.В. Особенности галопирующей детонации в сверхзвуковом потоке горючей смеси под слоем инертного газа // Изв. РАН. Механика жидкости и газа. 2010. №5. С. 167–175.
22. Левин В.А., Мануйлович И.С., Марков В.В. Формирование детонации во вращающихся каналах // ДАН. 2010. Т. 432, №6. С. 775–778.
23. Левин В.А., Мануйлович И.С., Марков В.В. Инициирование детонации при вращении эллиптического цилиндра внутри кругового цилиндра и деформировании стенок канала // Прикл. механика и техн. физика. 2010. Т. 51, №4. С. 17–25.
24. Левин В.А., Мануйлович И.С., Марков В.В. Математическое моделирование ударно-волновых процессов при взаимодействии газов с твердыми границами // Тр. МИАН. 2013. Т. 281. С. 42–54.
25. Левин В.А., Мануйлович И.С., Марков В.В. Численное моделирование спиновой детонации в каналах круглого сечения // ЖВМиМФ. 2016. Т. 56, №6. С. 1122–1137.
26. Быковский Ф.А., Ждан С.А. Современное состояние исследований непрерывной детонации топливовоздушных смесей (обзор) // Физика горения и взрыва. 2015. Т. 51, №1. С. 31–46.
27. Воеводин Вл., Жуматий С., Соболев С., Антонов А., Брызгалов П., Никитенко Д., Стефанов К., Воеводин Вад. Практика суперкомпьютера “Ломоносов” // Открытые системы. СУБД. 2012. №7. С. 36–39.
28. Термодинамические свойства индивидуальных веществ / Под ред. В.П. Глушко и др. М.: Наука, 1978. Т. I, кн. 2.
29. Westbrook C.K., Dryer F.L. Chemical kinetic modeling of hydrocarbon combustion // Prog. Energy Combust. Sci. 1984. V. 10, N 1. P. 1–57.
30. Годунов С.К., Забродин А.В., Иванов М.Я., Крайко А.Н., Прокопов Г.П. Численное решение многомерных задач газовой динамики. М.: Наука, 1976.