# Theory of Solid-Propellant Nonsteady Combustion

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# Theory of Solid-Propellant Nonsteady Combustion

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# About the Authors

## Professor Boris V. Novozhilov

Professor Boris V. Novozhilov (1930–2017) was born in Alma-Ata (Kazakhstan, which at that time was part of the Soviet Union). He graduated with honors in Applied Physics from the Leningrad (currently Peter the Great St. Petersburg) Polytechnic Institute in 1953. He received his PhD (1959) and DrSc (1968) degrees in Physical and Mathematical Sciences.

From 1954 to 2017, Professor B.V. Novozhilov worked at the Institute of Chemical Physics (currently the Semenov Institute of Chemical Physics) of the USSR (later Russian) Academy of Sciences in various roles, including the Head of Laboratory of Mathematical Methods in Chemical Physics (1976–1992) and Chief Researcher.

Professor B.V. Novozhilov is best known for his outstanding fundamental contribution to the theory of propellant combustion and, together with Ya. B. Zeldovich, is a founder of the Zeldovich–Novozhilov theory of nonsteady solid propellant combustion.

Professor B.V. Novozhilov's other research interests include nuclear physics (propagation of gamma quanta in matter), the theory of spin combustion, and the theory of “cold” flame propagation.

Professor B.V. Novozhilov is a recipient of the Ya. B. Zeldovich Gold Medal from The Combustion Institute “for outstanding contributions to the theory of combustion” (1996). He has also received a number of Russian Federation Government Awards in Science and Technology.

Professor B.V. Novozhilov is the author of over 150 journal papers and 12 books.

## Professor Vasily B. Novozhilov

Professor Vasily B. Novozhilov was born in 1963 in Moscow. He graduated with an MSc in Applied Mathematics from the Russian State University of Oil and Gas in 1986. He later received a PhD in Physical and Mathematical Sciences (Mechanics of Fluid, Gas and Plasma) from the Moscow Aviation Institute in 1993.

Professor V.B. Novozhilov held research positions at the Russian Academy of Sciences (Institute for Problems in Mechanics) and the University of Sydney. Furthermore, he held academic appointments at Nanyang Technological University (Singapore), as a Professor in Fire Dynamics at The University of Ulster (UK), and as a Professor of Mathematics at Victoria University (Australia). From 2014 to 2017 he was a Director of the Centre for Environmental Safety and Risk Engineering at Victoria University, Australia.

Major research interests of Professor V.B. Novozhilov include combustion (solid propellants, combustion theory and fire research) and the theory of heat transfer. He is a leading expert in theoretical and computational methods in the areas of combustion and fire research, in particular, computational fluid dynamics modelling of compartment fires. He has also made important contributions to the application of dynamical system methods in fire dynamics, and has also been greatly involved with analytical methods of the heat transfer theory in application to ultra-fast heat transfer processes.

Professor V.B. Novozhilov is the author of over 60 journal papers and four book chapters. He was a Keynote Speaker at the 68th International Astronautical Congress (2017) delivering an overview of the fundamentals of the Zeldovich–Novozhilov propellant combustion theory, as well as of other contributions by Professor B.V. Novozhilov to the physics of combustion.

# Preface

Nonsteady operating regimes, where fuel burning rates vary in time, are common for solid rocket motors. Under such conditions, combustion chamber pressure and, consequently, specific impulse are also functions of time. Some examples of such processes are combustion under variable pressure, a transition from one operating regime to another, oscillating combustion, erosion combustion in a dynamical regime, and propellant charge ignition and extinction under rapid depressurization.

In contrast to a steady-state regime, propellant burning rate in such situations depends not only on instantaneous parameters (initial pressure, temperature, and the velocity of a tangential gas stream), but is also determined by the full history of the process. This is due to the inertia of the combustion wave, which includes a heated layer of the condensed phase, a chemical reaction zone, and a certain region in space that is occupied by combustion products.

The natural way of describing nonsteady propellant combustion would be to use the theory of steady-state burning regimes. The transition to unsteady theory would require a simple addition of time derivatives into the relevant set of differential equations. At the current level of available computational resources, this additional mathematical complexity does not present a problem. However, the described hypothetical approach is not possible for a very simple reason: the consistent and universal theory of steady-state propellant combustion describing experimental observations does not exist.

Each physical and chemical process which occurs during the combustion of propellants is immensely complex. For the overwhelming majority of substances, the burning rate is determined by chemical kinetics. Therefore, the kinetic parameters of reactions are a substantial part of practically any combustion theory. However, with some exception, this knowledge of the kinetics of combustion reactions is as yet incomplete. In particular, information on chemical transformations which occur during the combustion of condensed substances is very scarce so it is necessary to involve model kinetic schemes, which only remotely resemble real chemical processes (typically, Arrhenius dependence on temperature and power dependence on reactant concentration are adopted).

There is a large body of steady-state homogeneous and composite propellant combustion models presented within this work. Naturally, such models contain a large number of parameters (reaction rate constants, activation energies, heat of combustion, transfer coefficients, thermophysical properties of gas, condensed phases, etc.) which are unknown in most cases. Evidently, an adjustment of numerous parameters allows the experimental data to be approximated, which of course does not imply a proper description of real fuel. Such studies are therefore of qualitative nature only, and are hardly suitable for comparison with experiments. Moreover, it would probably be impossible to develop a quantitative steady-state combustion theory applicable to a wide range of substances due to the large variation in their properties.

A drastically different approach to the development of nonsteady theory (avoiding the necessity to create a detailed description of the steady-state regime) was proposed by Ya.B. Zeldovich in 1942. It invokes an elegant and powerful idea of using the experimentally determined steady-state dependence of a propellant burning rate on pressure and an initial temperature for studying nonsteady combustion regimes. It was demonstrated that this is only possible taking into account the thermal inertia of the condensed phase. The idea was formulated in the original paper by Zeldovich (1942) in the following way: ‘Since the relaxation time of combustion in gas is very small, we have the right to consider gaseous combustion as determined by the thermal condition of the thin condensed phase layer adjacent to the interface; the temperature distribution within deeper layers does not have a direct effect on the processes near the surface. The conditions of gas must be fully determined by instantaneous values of the surface temperature, and a temperature gradient in the condensed phase at the surface. Consider the surface temperature as being constant.’

Thus, the nonsteady propellant combustion theory was reduced to a consideration of a relatively slow variation of temperature distribution in the condensed phase. This is achieved by the solution of the heat transfer equation, combined with the known dependency of the burning rate on instantaneous values of pressure and the temperature gradient in a condensed phase at the surface. The latter may be obtained from the (theoretical or experimental) steady-state dependency of the burning rate on pressure and initial temperature.

This theory explained some nonsteady combustion phenomena qualitatively, but its quantitative comparison with experimentation leads to contradiction. Most remarkably, this contradiction manifests itself in the conclusion that, according to this theory, a steady-state burning regime of real systems is actually unstable. The reason for this discrepancy is an oversimplification of the theory, which considered propellant surface temperature as constant.

For all practically used compositions, the temperature at the interface between the condensed and gas phases