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**Physics of Shock Waves
and High-Temperature
Hydrodynamic Phenomena**

Volume II

Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena

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Volume II

Translated by Scripta Technica, Inc.



ACADEMIC PRESS
New York and London
1967

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ACADEMIC PRESS INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS INC. (LONDON) LTD.
Berkeley Square House, London W.1

LIBRARY OF CONGRESS CATALOG CARD NUMBER: 66-29390

PRINTED IN THE UNITED STATES OF AMERICA

Editors' foreword

The lack of a comprehensive book on high-temperature physical gasdynamics has been felt for a long time. Since we wrote the first edition of "Hypersonic Flow Theory" we have particularly felt the need for a complementary text covering this field. A few books in the field have appeared, treating some of the pertinent topics. The brilliant text of Zel'dovich and Raizer first appeared early in 1964, and was not only outstanding but completely unique. The revised and updated second edition of this text is presented here in English, shortly after the Russian version. We hope that these two volumes together with the second edition of our own "Hypersonic Flow Theory" will serve to present a comprehensive picture of high-temperature high-speed flows in both their physical and hydrodynamical aspects. Our second edition will be in two volumes, the first on Inviscid Flows already published, and the second on Viscous and Rarefied Flows planned for 1969.

Zel'dovich and Raizer's text is truly comprehensive in the field of high-temperature gasdynamics, dealing thoroughly with all the essential physical aspects and their influence on the dynamics and thermodynamics of continuous media. The authors bring a deep physical insight to bear in explaining the nature of seemingly most complicated phenomena. Mathematical and formal treatments are kept to a minimum, while the results of such treatments are reported and compared with those of simplified approaches. The actual scope of the text is discussed in the authors' prefaces.

The standard approach of the theoretical physicist for many of the subjects treated here is quite formal, and not readily connected in the student's mind with physical ideas. Relatively rare are approaches which are correct in essentials and which are based upon sound physical reasoning from fundamental concepts. It is here that this text excels and is unduplicated. The authors consistently explain the physical phenomena of interest on the simplest correct physical basis, using classical instead of quantum physics where this is possible.

As an inevitable consequence of the comprehensive nature of the text, it is a large one. In the English version we have been forced to split the work

into two volumes. This split is a fairly natural one, however, as the first volume covers primarily the fundamental hydrodynamic, physical, and chemical processes involved; the second volume covers primarily the application and interaction of these processes in a multitude of important problems. However, the two volumes together certainly constitute a fully integrated and interrelated work.

It is truly difficult to qualify the audience to which this work is directed. Our physicist colleagues who have used parts of the book in class have found it exceptionally well adapted to teaching in graduate courses. At the same time, they, like the editors, have learned from the book and have obtained a better appreciation for the subject as a whole. The book is also ideally suited for engineers, presenting for them not only the basis for acquiring the physical understanding they need, but also specific formulas, methods, and experimental results for use in making practical calculations. Thus, without exaggeration, we can say that it is well suited to researchers, engineers, students, and professors. In a word, the authors have succeeded in the aims set forth in their original preface.

The authors are thoroughly acquainted with the world literature, and the references cited are comprehensive. The Soviet journals cited are mostly those now regularly translated into English, so that very few of the references cited in this edition are to be found only in Russian.

The editors are grateful for the close and friendly cooperation of the authors. We have exchanged comments, clarifications, and lists of errata. Some editorial changes have been incorporated with the authors' consent. Where it was thought helpful to indicate a different point of view on a topic, to discuss terminology, or occasionally to amplify a statement, we have added an editors' footnote. Subject and author indexes have been added, covering Volume I at the end of that volume, and covering both volumes at the end of Volume II.

The editors gratefully acknowledge the financial support and assistance of the Advanced Research Projects Agency through a contract technically administered by the Fluid Dynamics Branch of the Office of Naval Research with the Massachusetts Institute of Technology. Without this support the editors would not have been able to carry out this project. For the main part of the translating we are indebted to Scripta Technica, Inc. We wish to thank Miss Margaret Gazan for her skillful handling of the secretarial work and of many editorial details. A number of our colleagues have given us valuable comments and corrections, for which we express our sincere thanks.

We also wish to thank Mezhdunarodnaya Kniga for furnishing us the figures. We express our most sincere appreciation to our publishers for their cooperative attitude in this endeavor.

Our warmest thanks go to the authors for their wholehearted cooperation in this undertaking.

September, 1966

WALLACE D. HAYES
RONALD F. PROBSTEIN

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Preface to the English edition

This book considers a large variety of problems of modern physics and engineering, which deal with shock waves, high temperatures and pressures, plasmas, strong explosions, very strong electrical discharges, interaction of intense laser radiation with a medium, etc. We have attempted not only to present the clearest possible interpretation of the physical bases of the phenomena arising in these fields, but also to give practical guidance to those who work with these subjects in science and modern technology.

The content of this book is determined to a large extent by the tastes of the authors. In particular, we have considered in more detail those phenomena and problems which were investigated by us personally. Naturally, more attention has been given to the work of Soviet authors. However, we have attempted to reflect in a sufficiently complete manner the work of American and British scientists, which has led to important advances in the solutions of the problems considered.

The text prepared by us for the English edition is almost identical with that of the second Russian edition, which is to be published in 1966. It contains important additions (and corrections) not contained in the first Russian edition of 1963.

We are very glad that this book has been translated into English and will become accessible to many foreign scientists and engineers. We are grateful to the translators for their work and value most highly the initiative of Professors Hayes and Probst, who have undertaken the editorship of the translation, have shown great care and thoroughness, and have made a number of valuable comments.

October, 1965

**YA. B. ZEL'DOVICH
YU. P. RAIZER**

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Preface to the first Russian edition

The requirements of modern technology have made it necessary for scientific research to penetrate into the domain of very high values of the state variables, such as with high concentrations of energy, very high temperatures and pressures, and extreme velocities. In practice, such conditions are encountered in strong shock waves, in explosions, in hypersonic flight of bodies in the atmosphere, in very strong electrical discharges, etc.

A great variety of physical and physical-chemical processes can occur in gases at high temperatures: excitation of molecular vibrations, dissociation, chemical reactions, ionization, and radiation of light. These processes affect the thermodynamic properties of gases, while at high velocities and with sufficiently rapid changes in the state of the fluid the rates of these processes also affect the motion of the fluid. Of special importance at very high temperatures are processes related to the emission and absorption of light and radiative heat transfer. The enumerated processes are of interest not only from the point of view of their energetic effect on the motion of the gas, but also frequently lead to changes in the composition of the gas and its electrical properties, to the emission of radiation from the gas and many optical phenomena, etc. An appreciable portion of this book is devoted to the study of all of these problems, comprising the newly-arisen branch of science termed "physical gasdynamics."

Of great scientific and practical interest is the study of strong shocks in solids. Recent achievements, which have permitted the compression of solid bodies by means of shock waves to pressures of millions of atmospheres, have opened new paths for the investigation of solid media at ultra-high pressures. Considerable attention has, therefore, been devoted to these problems in the present book.

Many scientific disciplines are interwoven here, including gasdynamics, shock wave theory, thermodynamics and statistical physics, molecular physics, physical and chemical kinetics, physical chemistry, spectroscopy, the general theory of radiation, the elements of astrophysics, and solid state physics. Many of the physical processes and phenomena considered are of differing character and are not directly related to each other. The result of such diversity in the material is the absence of obvious continuity in the

contents of the book. Certain chapters are quite independent, and deal with completely different areas of physics or mechanics, so that not all chapters are related to each other. Hence, the reader interested in one or another particular topic will find it sufficient to become acquainted only with the corresponding chapters.

In examining the most diverse problems, even those of mathematical character, we endeavored primarily to explain the physical essence of the phenomena using the simplest mathematical tools, frequently resorting to estimates and semiquantitative analysis. At the same time, we attempted to help those physicists, fluid mechanics, and engineers who work in the corresponding areas of applied physics and engineering, and to supply them with practical tools for independent analysis of many different and complex physical phenomena. For this purpose, the treatment of the majority of the phenomena examined is carried through to specific numerical results, the formulas for the calculation and evaluation of various quantities are presented in a convenient form for practical work, a large amount of useful experimental data and reference material is cited, etc.

The book is of a theoretical character and the description of experimental apparatus and methods is kept to a minimum. However, the presentation and comparison of experimental results with theoretically predicted values has been given an appropriate amount of attention.

The journal literature in "physical gasdynamics" is immense. As far as we know, however, no attempt has been made, either in the Soviet Union or elsewhere in the world, to present a systematic and generalized exposition — in a single book and from a single point of view — of the material in this new area of science. Apparently this book is the first attempt in this direction.

The literature cited in the text reflects the fact that the book was written during 1960 and 1961. However, references to more recent works and brief additions were added in those sections dealing with problems which are being developed at an especially rapid pace. This refers primarily to Chapters V, VI and VII.

The great variety of the phenomena and the large scope of the material forced us to limit the presentation to far from all the problems related to the vast area under consideration. We have not considered the more mathematical aspects of hydrodynamics, nor such problems as that of supersonic flow past bodies. We have only barely touched upon electromagnetic phenomena, and have not dealt at all with thermonuclear fusion, behavior of a plasma in a magnetic field, nor magnetohydrodynamics and magnetogasdynamics, combustion, detonation, etc. A great many books dealing with such problems are already available.

The selection of the material for the book has been to some extent a subjective one. A significant place in the text is devoted to phenomena which were investigated by the authors in their own studies. Thus, the authors' original works have served as a basis for part of the text — almost completely in Chapters VIII and IX, to a considerable extent in Chapters VII, X and XII, and partially in Chapter XI. Chapter I represents a complete revision of an earlier book by one of the authors, "Theory of Shock Waves and Introduction to Gasdynamics," published by the Academy of Sciences of the USSR in 1946.

We should like to express our especial gratitude to A. S. Kompaneets, who is responsible for working out a number of problems dealt with in the book and for many useful criticisms and remarks on the manuscript. We are grateful to L. B. Altshuler and S. B. Kormer for their remarks on the manuscript for Chapter XI, which is based on their work to a large extent. We are also grateful to M. A. El'yashevich who read the manuscript carefully and made valuable comments.

YA. B. ZEL'DOVICH
YU. P. RAIZER

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Preface to the second Russian edition

The general structure of the book and the major part of the text in this second edition were retained without change. At the same time, certain chapters were thoroughly revised and a considerable amount of new material was added. Chapter V now contains a part devoted to breakdown (high-intensity ionization) processes and to the heating of gases by a focused laser beam. This is one of the most interesting phenomena connected with the interaction between an intense light beam and a medium. It was discovered experimentally several years ago, shortly after the development of lasers, which produce high pulse intensities measured in tens of megawatts and higher, and immediately attracted the attention of many physicists (including the authors of this book, who have published works on the theory of this phenomenon).

In connection with problems of gas ionization by laser radiation we have added sections to Chapter V in which emission and absorption of light by free electrons on collision with neutral atoms is considered. The lively interest which is now shown toward lasers has induced us to write a special section (in Chapter II) devoted to the semiclassical treatment of induced emission and of the laser effect.

Extensive changes were made in Part 3 of Chapter VI, in which we consider problems of ionization, recombination, and electronic excitation. This part has been virtually rewritten and extensively expanded in order to take into account modern views on these processes. According to these views an important role is played by stepwise ionization of atoms (first excited and then ionized) and electron capture into upper atomic levels through three-body collisions with subsequent deexcitation of the excited atoms through electron impact and radiative transition. Ionization in air has been considered in more detail. The presentation of the closely related problem of ionization of a gas in a shock wave (in Chapter VII) was also changed.

Sections of Chapter VIII, pertaining to the rate of change in the degree of ionization and of the "freezing" accompanying a sudden expansion of an ionized gas into a vacuum have been rewritten. This problem has been recently reexamined with account taken of electron capture into upper

atomic levels as a result of recombination through three-body collisions.

On the basis of material which was contained in the first edition and of more recent results we have added in Chapter XII a part dealing with the propagation of shock waves in an inhomogeneous atmosphere with an exponential density distribution. We have added an appendix wherein are collected certain constants, relations between atomic constants, and relations between units and formulas which are frequently encountered in practice when dealing with the subject matter of this book.

We have here mentioned only the principal, but by far not all of the changes and additions which were made (we also note that mistakes and printing errors which were found in the first edition have been corrected).

Topics of physics and mechanics which were touched upon in the book are developing at an extremely rapid rate, with the consequent discovery of more and more new fields of application (an example of this is the phenomenon of breakdown and heating of gases in the focus of a laser beam).

As an evidence of the interest shown toward these scientific disciplines we cite the fact that immediately after publication of this book, an English translation was undertaken in the United States, and a need for a new edition very soon arose. We hope that this second revised and supplemented edition will be of use to specialists already working in the above fields of science and engineering and to those who are about to enter these fields.

YA. B. ZEL'DOVICH
YU. P. RAIZER

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