THE DETONATION PHENOMENON

This book introduces the detonation phenomenon in explosives. It is ideal for engineers and graduate students with a background in thermodynamics and fluid mechanics. The material is mostly qualitative, aiming to illustrate the physical aspects of the phenomenon. Classical idealized theories of detonation waves are presented first. These permit detonation speed, gas properties ahead and behind the detonation wave, and the distribution of fluid properties within the detonation wave itself to be determined. Subsequent chapters describe in detail the real unstable structure of a detonation wave. One-, two-, and three-dimensional computer simulations are presented along with experimental results using various experimental techniques. The important effects of confinement and boundary conditions and their influence on the propagation of a detonation are also discussed. The final chapters cover the various ways detonation waves can be formed and provide a review of the outstanding problems and future directions in detonation research.

Dr. John H. S. Lee is a professor of mechanical engineering at McGill University. His research areas are in combustion, detonations and shock wave physics, and explosion dynamics; he has been carrying out fundamental and applied research in these areas for the past 40 years. He is a consultant and has served on numerous government and industrial advisory committees on explosion hazards and safety since the late 1960s. He is a recipient of the silver medal from the Combustion Institute (1980), the Dionizy Smolenski Medal from the Polish Academy of Sciences (1988), and the Nuna Manson gold medal (1991) for his outstanding contributions to the fundamentals and applied aspects of explosion and detonation phenomena. He is also a two-time recipient of the Faculty Outstanding Teaching Award (1989 and 1995), was elected an honorary professor of the Institute of Mechanics of the Chinese Academy of Sciences (2003), and received the Outstanding Alumni Award of the Polytechnic University of Hong Kong (2003). He is a Fellow of the Royal Society of Canada.

THE DETONATION PHENOMENON

JOHN H. S. LEE

McGill University

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521897235

First published 2008

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Lee, John H. S., 1938–
The detonation phenomenon / John H.S. Lee.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-89723-5 (hardback)
1. Detonation waves. 2. Detonation waves – Computer simulation.
3. Explosives. I. Title.
QC168.85.D46L44 2008
662′.2 – dc22 2008000517

ISBN 978-0-521-89723-5 hardback

to Julie

Contents

Preface

Explosives are highly energetic substances with fast reaction rates and can be in gaseous, liquid, or solid form. Chemical reactions can propagate through the explosive at high supersonic speeds as a detonation wave: a compression shock with an abrupt increase in the thermodynamic state, initiating chemical reactions that turn the reactants into products. This book is devoted to a description of the detonation phenomenon, explaining the physical and chemical processes responsible for the self-sustained propagation of the detonation wave, the hydrodynamic theory that permits the detonation state to be determined, the influence of boundary conditions on the propagation of the detonation, and how detonations are initiated in the explosive.

The book is concerned only with detonation waves in gaseous explosives, because they are much better understood than detonations in condensed phase media. There are many similarities between detonations in gaseous and in condensed explosives, in that the detonation pressure of condensed explosives is much higher than the material strength of condensed explosives and the hydrodynamic theory of gaseous detonations is applicable also to condensed phase detonations. However, material properties such as heterogeneity, porosity, and crystalline structure can play important roles in the initiation (and hence sensitivity) of condensed explosives.

It is perhaps impossible to be entirely objective in writing a book, even a scientific one. The choice of the topics, the order of their presentation, and the emphasis placed on each topic, as well as the interpretation of theoretical and experimental observations, are bound to reflect the author's views. In an attempt to render the book readable for beginners, I have omitted topics that are mathematically complex (e.g., stability theory) or have given only a qualitative discussion of them.

I intend the book to be accessible to those with an undergraduate background in fluid mechanics and thermodynamics. Thus, this book is not a comprehensive treatment of detonation science, and many important topics have been omitted or given only superficial coverage. I have also refrained from giving a complete bibliography, for I feel that in the age of the internet, readers can readily search for relevant references on any topic they wish to pursue further.

I have not reviewed the extensive literature in the field and discussed the contributions of many of my colleagues for a balanced view of the subject. However, I have learned a great deal from all the researchers in the field, past and present; to all of them, I owe a great debt. In particular, I would like to mention that the detonation phenomenon is particularly fortunate in having had perhaps the world's best physicists and chemists working on the subject during the two world wars (Richard Becker, Werner Döring, G. I. Taylor, John von Neumann, George Kistiakowsky, John Kirkhood, Yakov Zeldovich, K. I. Schelkhin, and many others). It is from their wartime and postwar publications that I first learned the subject. I also have to acknowledge the strong influence of an international group of detonation researchers in my formative years in the early 1960s (e.g., Don White, Russell Duff, Gary Schott, Tony Oppenheim, Roger Strehlow, Numa Manson, Hugh Edwards, Rem Soloukhin, and Heinz Wagner). They took me as a junior colleague and mentored my development. T. Y. Toong is responsible for initiating me into scientific research. Even though I did not spend much time under his guidance, he set a lasting example of scholarship that I have always tried to follow throughout my career.

The person to whom I am most indebted in getting the manuscript finished and ready for publication is Jenny Chao. She spent endless hours proofreading and revising the various versions of the manuscript. Without her dedication, I doubt this book would ever have been ready for publication. Eddie Ng also contributed a lot to this book. I have drawn heavily from his Ph.D. dissertation in the chapters on the detonation structure, instability, and blast initiation. Both Jenny and Eddie deserve more than the usual "thank you," for it is their dedicated effort that turned my manuscript into this book. Steven Murray and Paul Thibault read the entire draft of the manuscript, pointed out errors, and gave valuable suggestions; Paul also spent many hours carefully proofreading the final proofs. Andrew Higgins and Matei Radulescu read selected chapters and offered useful comments. Jeff Bergthorson's thorough review of the copyedited manuscript resulted in a significant improvement of this book. It is not possible to incorporate everybody's suggestions, but I want to assure them that that is not because I chose to ignore their advice. There is a limit to how many times one can make changes to a manuscript.

I would also like to thank Christian Caron for encouraging me to start this effort, assuring me that a personal story of the phenomenon is acceptable for publication. The enthusiastic support and encouragement from Peter Gordon in the final process of revision and publication of the book is very much appreciated. I find that writing a book is a humbling experience.

Finally, I would like to acknowledge the essential indirect contributions of Julie, Julian, Leyenda, Heybye, and Pogo in providing a loving environment of fun and laughter outside of scientific work.