ROCKET PROPULSION

A modern pedagogical treatment of the latest industry trends in rocket propulsion, developed from the authors' extensive experience in both industry and academia.

Students are guided along a step-by-step journey through modern rocket propulsion, beginning with the historical context and an introduction to top-level performance measures, and progressing to in-depth discussions of the chemical aspects of fluid flow combustion thermochemistry and chemical equilibrium, solid, liquid, and hybrid rocket propellants, mission requirements, and finally to an overview of electric propulsion.

Key features include:

- A wealth of homework problems, with a solutions manual for instructors online.
- Numerous real-life case studies and examples.
- An appendix detailing key numerical methods, and links to additional online resources.
- Design approaches for all types of chemical rockets (including solid, liquid, and hybrid propellants) and electric propulsion.
- Techniques for analysis of engine and motor operation, and system and vehicle level performance.

This is a must-have book for senior and first-year graduate students looking to gain a thorough understanding of the topic along with practical tools that can be applied in industry.

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CAMBRIDGE
UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

79 Anson Road, #06–04/06, Singapore 079906

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108422277
DOI: 10.1017/9781108381376

First published 2019

Printed in the United Kingdom by TJ International Ltd, Padstow Cornwall

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

Library of Congress Cataloging-in-Publication Data
Names: Heister, Stephen D., author. | Anderson, William E. (William Edward), author. | Pourpoint, Timothee (Timothee Louis), author. | Cassady, R. Joseph, (Joe), author.
Title: Rocket propulsion / Stephen D. Heister (Purdue University, Indiana), William E. Anderson (Purdue University, Indiana), Timothee Pourpoint (Purdue University, Indiana), Joseph Cassady (Aerojet Rocketdyne).
Description: First edition. | New York : Cambridge University Press, [2018] | Includes bibliographical references.
Identifiers: LCCN 2018036914 | ISBN 9781108422277
Subjects: LCSH: Rockets (Aeronautics) | Jet propulsion. | Rocket engines.
Classification: LCC TL782 .H45 2018 | DDC 621.43/56–dc23
LC record available at https://lccn.loc.gov/2018036914

ISBN 978-1-108-42227-7 Hardback

Additional resources for this publication at www.cambridge.org/heister.

Cambridge University Press
978-1-108-42227-7 — Rocket Propulsion
Stephen D. Heister , William E. Anderson , Timothée L. Pourpoint , R. Joseph Cassady
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PREFACE

Background

While its roots extend back centuries, the modern foundations of chemical propulsion were developed in the World War II era and in a bit more than two short decades later these systems pushed American astronauts to the moon. The engineering challenges for the development of these systems are numerous because the volumetric energy release is perhaps the highest of any device constructed by humans. This factor, combined with the need to minimize weight for devices that are being flown, leads to a demanding set of requirements for engineers. As a result, the knowledge set required to contribute in this field demands a broad set of considerations including combustion, single and multiphase fluid flow, material properties and compatibility, structural analysis, and design as important considerations.

This textbook grew out of course notes I developed over a 20-plus year period after joining Purdue in 1990. Purdue already had had two chemical rocket propulsion courses on its books at that time: a senior-level course (AAE439) that parallels those taught in other aerospace engineering schools around the globe, and a more unique graduate-level treatment (AAE539). The AAE439 notes have been published locally on an informal basis and have provided an opportunity to correct the many errors that inevitably creep in in a document of this size. The graduate course was initially developed by my predecessor, Professor Robert Osborn. This course delved heavily into solid rocket propellant combustion – Osborn's main area of research over his storied career. Given the broader needs of the community, I set out to include liquid and hybrid propulsion as well. At present, about half of the graduate-level material from AAE539 is included in the book. Perhaps my colleagues and I will add more of this material in future editions if market interest and energy of the authors so warrant. Other than this limitation, I believe that the text is up to date at this point with the latest information on new vehicles under development and the role that additive manufacturing is playing in our industry.

Main Features of This Book

This text was developed for propulsion *students* and the tone of the book emphasizes the tutorial nature of this task. I strongly believe that engineering students learn material by working problems; nearly 300 are included in the book for this purpose. Many of these problems are analogous to a cursory analysis that might be done by a practicing engineer in industry and many are motivated by the authors' collective experience of issues and studies performed in industry. The abundance of practice material distinguishes this text from those that are currently available or have been published over the years. Chapters 9, 10 and 12 are exceptions in this regard. It is difficult to assign homework problems on liquid propellants and the combustion instability topic is more advanced and not typically something we would assign students in coursework. The turbomachinery chapter came together over the last year or so and we are currently building up the problem database in that area.

My co-authors and I made another conscious decision to emphasize analytic approaches to problems in order to arm students with tools that they might apply in an industrial career. Even in this modern computer age with numerous multidimensional computer codes, it is often useful to check results against a simpler zero or one-dimensional result and in doing so gain insight into the complexity of the problem at hand.

Course Prerequisites and their Rationale

A student in a course that uses this book should already have taken thermodynamics and compressible fluid flow courses that are typically taught in sophomore and junior years in aerospace engineering curricula. Knowledge of sophomore-level calculus is also assumed. While many students in mechanical engineering or combined ME/AE programs gain background in heat transfer, this subject is absent from many AE schools and for that reason a focused attempt is made to provide top-level principles in Chapter 6 of the book. This material is not intended to replace a full semester course in heat transfer, but to motivate for more formal coursework in the area and to provide some background on rocket-related analyses that are commonplace in our industry. Because heat transfer is an integral performance element in a staged combustion rocket engine, it is really necessary to provide a sufficient level of detail such that students understand the fundamentals of this broad area. The broad topic of combustion is addressed similarly and focuses on specific approaches that are used in the rocket industry. Here at Purdue, we encourage all our propulsion students to try to get additional coursework in the combustion and heat transfer fields due to their importance in our profession.

Structure of the Book

As I formulated a plan toward manuscript development, it became apparent that my colleagues here could strengthen the work substantially. I engaged Bill Anderson and Tim Pourpoint early on, to improve the book and specifically to add material in combustion instability and liquid rocket propellants per their extensive expertise in these areas. Bill helped in many other ways and made suggestions/improvements to numerous chapters. We also engaged long-time friend and Purdue alumnus Joe Cassady to provide valuable input on electric propulsion. With a 30-plus year career at Aerojet Rocketdyne, and substantial experience developing educational materials, he was a natural choice.

We open with a brief history of rocketry and introduce the types of rocket propulsion systems commonly in use today. Chapters 2 and 3 contain material on mission requirements and trajectory analyses that are not strictly germane to the propulsion student, but we like to have the student have an understanding of how the propulsion analyst works with mission/trajectory designers in a real-world application. This approach also allows one to conduct simple sizing exercises without running to mission design experts, thereby providing a comprehensive capability for the student.

Chapter 4 provides fundamentals of compressible flow through nozzles with a review of nozzle design alternatives and treatment of flow separation, two-phase flow, and a brief discussion of method of characteristics. Chapter 5 provides classical introduction to combustion thermochemistry with a large number of examples to work out chemical equilibrium by hand in order to gain perspective for use of our standard industry computer codes. Chapter 6 provides introductory background on heat transfer and a focused discussion on some of the more important problems facing the rocket propulsion analyst.

Chapters 7–11 provide in-depth discussion of solid, liquid, and hybrid rocket propulsion systems. An entire chapter (Chapter 9) is dedicated to liquid propellants for liquid rocket or hybrid propulsion systems. Turbomachinery discussions are also broken out into a dedicated chapter (Chapter 10). Once again, the emphasis in these chapters is to provide students with analytic approaches to computing behaviors of a given design and propellant selection. Particular emphasis is placed on problems that we still struggle with as a community in order to provide students with a glimpse of the issues they will face as they enter the field.

Chapter 12 is Bill's extended discussion on one of our most vexing topics: combustion instability. In addition to providing overviews of the problem, design guidelines for achieving stability, and methods for measurement and rating, an introduction to linear analysis necessary to understand the most common techniques in use today is covered in some detail. Admittedly, this is higher-level material and would certainly be omitted in a first course in most instances.

Finally, we close out the book with Joe's perspectives on electric propulsion in Chapter 13. As with the chemical propulsion discussion, he provides perspective on the "hard problems" faced by the EP community.

A single appendix is included in the text. We defer to our modern age by including a list of website links rather than reams of paper that regurgitate the compressible flow and thrust coefficients typically seen in a text of this nature. We believe this is a superior way to access these things in today's highly connected environment. Numerous other links are also included and the entire list of links is provided on our Purdue Propulsion Web Page (https://engineering.purdue.edu/~propulsi/propulsion/). In addition, substantial background is provided on numerical methods that are required to solve some of the homework problems in the text. We wanted the book to stand on its own in this regard as many of our students have little or no experience in these methods when they enter our classroom.

ACKNOWLEDGMENTS

We have had the help of countless Purdue students over the years in “debugging” the problems we have constructed, and we are most grateful to this esteemed group. In particular, our teaching and research assistants have served a pivotal role in this venture. In fact, some of the problems have been formulated as a result of interactions with these individuals who now hold responsible positions within the US rocket propulsion industry. A few specific contributors who are current students or recent graduates include Nate Byerly, Dr. Jim Hilbing, Dr. Brandon Kan, Jenna Humble, Dr. Enrique Portillo, Dr. David Stechmann, Dr. David Reese, Gowtham Tamananpudi, Stephen Kubicki, and Chris Zascek.

In addition, we are indebted to colleagues at NASA and in industry who have aided immensely in the compilation of the text. Specifically, Jim Goss, Dean Misterek, Chad Schepel, Ken Miller, Matt Smith, and Tom Feldman of Blue Origin provided invaluable guidance. Dr. John Tsohas, Sam Rodkey, and Jon Edwards at SpaceX have also provided help with images and editing. James Cannon at NASA MSFC also provided useful inputs on turbomachinery as did Bill Murray at Ursa Major Technologies. We thank Gerald Hagemann of Ariane Group for his guidance on nozzles. Also thanks to Andy Hoskins and Roger Myers of Aerojet Rocketdyne for helpful discussions on some of the electric propulsion materials. And to Frank Curran for sharing some charts from his AIAA short course.

We thank three very important people who had a large role in typing, re-typing, formatting, and re-formatting the numerous versions of original course notes that eventually became this text. Sharon Wise typed much of the early notes in the antiquated TRoff software. More recently, Leslie Linderman and Audrey Sherwood helped with the current version that was eventually sent to our capable publishers at Cambridge Press. We thank these women for their efforts.

Finally, as we approach the 50th anniversary of the historic lunar landing, we leave you with an image of undergraduate student Neil Armstrong as a source of inspiration for all who wish to help mankind travel to space.