The renewed interest in high-speed propulsion has led to increased activity in the development of the supersonic combustion ramjet engine for hypersonic flight applications. In this flight regime, the scramjet engine’s specific thrust exceeds that of other propulsion systems. This book, written by a leading researcher, describes the processes and characteristics of the scramjet engine in a unified manner, reviewing both theoretical and experimental research. The focus is on the phenomena that dictate the thermo-aerodynamic processes encountered in the scramjet engine, including component analyses and flow-path considerations; fundamental theoretical topics related to internal flow with chemical reactions and nonequilibrium effects, high-temperature gas dynamics, and hypersonic effects are included. Cycle and component analyses are further described, followed by flow-path examination. Finally, the book reviews the current experimental and theoretical capabilities and describes ground-testing facilities and computational fluid dynamic facilities developed to date for the study of time-accurate, high-temperature aerodynamics.

After completing his Ph.D. at the University of Virginia in 1991, Corin Segal took a teaching position at the University of Florida in the Mechanical and Aerospace Department, where he now leads research in the Combustion and Propulsion Laboratory. Prior to his graduate studies, Dr. Segal spent more than 11 years in the aerospace industry as a senior aerodynamicist and project manager and as a leader of the technical bureau. His current research at the University of Florida covers a range of topics, including mixing and combustion in high-speed flows, supercritical mixing, high-pressure combustion, and cavitation. Results of his group’s research have appeared in national and international publications. Dr. Segal is an associate editor of the AIAA Journal of Propulsion and Power and an associate Fellow of AIAA.
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PROCESSES AND CHARACTERISTICS

Corin Segal
University of Florida
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Preface

There is, justifiably, a great interest currently in the study and development of scramjet engines for hypersonic flight applications. A major impetus is the potential to reduce space accessibility costs by use of vehicles that use air-breathing propulsion from takeoff to the edges of the atmosphere; defense applications for hypersonic flight within the atmosphere are also of considerable interest. In the hypersonic flight regime, commonly considered to begin when velocities exceed Mach 6, the scramjet engine’s specific thrust surpasses that of any other propulsion system. Subsonic combustion, which technologically is easier to manage with the current knowledge, would be associated, in the hypersonic regime, with high stagnation temperatures that would lead to unacceptable dissociation levels, and hence an inability to materialize the energy rise expected through chemical reactions. Additional thermal and structural considerations preclude the use of other air-breathing propulsion systems at these flight velocities.

In the late 1950s, when scramjet research began, the development of this type of engine proceeded with varying degrees of intensity, as the national interests of the times drove investment levels. The past decade has seen increased enthusiasm in all sectors because of the expansion of government-funded scramjet research and numerous national and international collaborations, and development has been buoyed by significant scientific and technological progress. Major activities at the national level and international collaborations exist in Europe, including Russia, and in Japan, Australia, and the United States. This increased activity produced a great deal of knowledge; yet, much of the information accumulated over the years through various programs lies in the classified or proprietary category, and it is subject to limited availability. Several printed compilations have brought together major aspects of the international scientific and technical developments in this field. In most cases these volumes consist of contributed articles that summarize research and program results, including component technologies, national programs, and theories resulting from these efforts. The
last major effort in this direction was the volume edited by E. T. Curran and S. N. B. Murthy in 2000 that completed a set of three volumes, started in 1990, dedicated to the subject. As the editors pointed out, only the last volume in the series was dedicated specifically to scramjet propulsion; it included contributions from researchers worldwide with updated reviews of national programs and their results.

This book is intended to offer the reader an introduction to the study of scramjet propulsion, including careful definitions of terms and a unified description of the processes and characteristics of the scramjet engine. This book reviews the major knowledge base that has been accumulated through years of theoretical and experimental research on topics relevant to scramjet propulsion. A previous volume with a similar organization, focused primarily introducing upper-level engineering students to the topic of hypersonic propulsion, was written by W. H. Heiser and D. T. Pratt more than a decade ago (Hypersonic Airbreathing Propulsion, AIAA Educational Series, J. S. Przemieniecki, editor, 1994). Considerable progress has been made in the intervening period. This book attempts to incorporate up-to-date advances made to understand the fundamental processes governing high-speed reacting flows and presents technological developments relevant to the scramjet engine.

Current developmental programs are briefly mentioned in the first chapter only to provide a general background of existing technological activities. The focus is on the phenomena that dictate the thermoaerodynamic processes encountered in the scramjet engine, including component analyses and flow-path considerations. Hence this book begins with theoretical background information pertaining to internal flow with chemical reactions and nonequilibrium effects, high-temperature gas dynamics, and hypersonic effects; trajectory, loads, and performance analyses are then reviewed, followed by cycle analyses. No single-engine cycle exists that can efficiently cover the whole range of a flight from takeoff to orbit insertion; therefore combined cycles are of particular interest for the design of the scramjet cycle. They are capable of providing the synergy required for increasing the efficiency of any individual propulsion cycle; therefore some of the more promising combined cycles are reviewed in the context of engine cycle analysis. Component analyses are further described, including inlets, nozzles, and isolators. The emphasis is then placed on the processes encountered in the combustion chamber. Current knowledge of injection, mixing, and mixing-combustion interactions is described, including some advanced modes of mixing enhancement, such as fuel preinjection upstream of the combustion chamber and reaction mechanisms for hydrogen and hydrocarbon compounds, including current reduced mechanisms for higher-order hydrocarbon fuels. Special attention is given to the structure of the recirculation region and the problem of flameholding,
Preface

which is one of the key elements in the development of a feasible scram-
jet engine. A review of ground-based testing facilities, their capabilities, and
applicability to the experimental study of scramjet engines follows. The con-
siderable levels of energy associated with the operation of scramjet engines
led to considerable difficulty in reproducing all the thermodynamic conditions
encountered in flight in ground-based facilities. Theoretical modeling of physi-
cal processes, including the treatment of unsteady and high-temperature aero-
dynamics, has made substantial progress in the past decade and resulted in
powerful computational fluid dynamic facilities. Finally, reviews of the current
theoretical capabilities and issues are covered.

This book has benefited from contributions made by many individuals.
There are many research collaborators to whom I am in particular debt for our
shared work. At Pratt & Whitney-Rocketdyne, Allen Goldman, Atul Mathur,
and Paul Ortwerth have been constant collaborators during my research. We
had numerous conversations, and they have, in many instances, clarified obser-
vations related to flameholding and heat-release interactions in our common
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issues and has made, over the years, many useful research suggestions. Aaron
Auslander from NASA Langley Research Center and I had long, edifying con-
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Gabriel Roy, who, as a friend and program manager, has guided my and oth-
ers’ research for more than two decades. His vision and sense of scientific
and technological relevance has led to the advancement of many propulsion
engineering topics later emulated by researchers at national laboratories, uni-
versities, and industrial institutions. Viatcheslav Vinogradov from the Cen-
tral Institute for Aviation Motors (CIAM) in Moscow, Russia, and I collab-
orated on several studies of hypersonic inlets with fuel preinjection, studies
of mixing enhancement using thin pylons, and supersonic combustion studies
with condensed- and gaseous-phase compounds. Joaquin Castro has made, on
many occasions, relevant suggestions regarding flameholding of gaseous and
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I am indebted to Wei Shyy for the friendship and encouragement he has
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work ethics and professional drive continue to be an inspiration to all of us
who had the privilege of being his colleagues. Above all, I owe my gratitude to
my wife, Anca, for her love and for the inspiration, the drive, the reason, the
comfort, and the joy she has always been for me.
List of Acronyms

AFRL/PRA      U.S. Air Force Research Laboratory/Aerospace Propulsion Office
AIM           aerothermodynamic integration model
APL           Applied Physics Laboratory
ATREX         Air Turbo Ramjet Expander Cycle
CCP           combined-cycle propulsion
CDE           concept demonstration engine
CIAM          Central Institute for Aviation Motors
CPS           combination propulsion system
CUBRC         CALSPAN-UB Research Center
DAB           diffusion and afterburning
DCSCTF        Direct-Connect Supersonic Combustion Test Facility (NASA)
DCTJ          deep-cooled turbojet
DNS           direct numerical simulation
ESOPE         Etude de Statoréacteur comme Organe de Propulseur Evolué (France)
ETO           Earth-to-orbit
FMS           force measurement system
GALCIT        Graduate Aeronautical Laboratories at the California Institute of Technology
GASL          General Applied Science Laboratory
Hifire        Hypersonic International Flight Research Experiment
HOTOL         horizontal takeoff and landing
HRE           Hypersonic Research Engine (NASA)
HTF           Hypersonic Tunnel Facility (NASA)
IFTV          incremental flight test vehicle
JAXA          Japan Aerospace Exploration Agency
JHU           Johns Hopkins University
Kholod        hypersonic flying laboratory (Russia)
## List of Acronyms

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<tr>
<td>LACE</td>
<td>liquid–air collection engine or liquid–air-cycle engine</td>
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<tr>
<td>LACRRE</td>
<td>liquid–air collection rocket–ramjet engine</td>
</tr>
<tr>
<td>LEA</td>
<td>flight experimental vehicle (Russia)</td>
</tr>
<tr>
<td>LEM</td>
<td>linear eddy-mixing</td>
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<tr>
<td>LEO</td>
<td>low Earth orbit</td>
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<tr>
<td>LES</td>
<td>large-eddy simulation</td>
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<tr>
<td>MCH</td>
<td>methylcyclohexane</td>
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<td>magnetohydrodynamic</td>
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<td>NRC</td>
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<tr>
<td>PDF</td>
<td>probability density function</td>
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<td>PLIFF</td>
<td>planar laser iodine-induced fluorescence</td>
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<td>Supersonic Combustion Ramjet Missile</td>
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<td>viscous upwind algorithm for complex flow analysis</td>
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