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978-1-108-48075-8 — Aerothermodynamics and Jet Propulsion
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Aerothermodynamics and Jet Propulsion

Get up to speed with this robust introduction to the aerothermodynamics principles underpinning jet propulsion, and learn how to apply these principles to jet engine components. This book is suitable for undergraduate students in aerospace and mechanical engineering, and for professional engineers working in jet propulsion. This textbook includes consistent emphasis on fundamental phenomena and key governing equations, providing students with a solid theoretical grounding on which to build practical understanding; clear derivations from first principles, enabling students to follow the reasoning behind key assumptions and decisions, and successfully apply these approaches to new problems; practical examples grounded in real-world jet propulsion scenarios illustrate new concepts throughout the book giving students an early introduction to jet and rocket engine considerations; and online materials for course instructors, including solutions, figures, and software resources, to enhance student teaching.

Paul G. A. Cizmas is Professor of Aerospace Engineering at Texas A&M University. Over the past 25 years, he has conducted research into numerical simulations of transport phenomena in propulsion systems covering a large range of topics, including reduced-order modeling, aeroelasticity, combustion, and computational fluid dynamics. He is a Fellow of American Society of Mechanical Engineers and an Associate Fellow of American Institute of Aeronautics and Astronautics.

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Brief Contents

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Preface

This textbook was developed from the course notes put together for the second-semester junior class, Aerothermodynamics and Propulsion, taught at Texas A&M University. This class is followed by two senior courses: Aerospace Propulsion, a jet engine design class, and Rocket Propulsion, a rocket engine design class. Although this textbook was not conceived for these design courses, it provides essential foundational knowledge for design. Fundamentally, the purpose of the book is to enhance the aerodynamics and thermodynamics background of students, and to enable them to apply this knowledge to understanding jet propulsion.

Aims of the Text

This text is written primarily for undergraduate students in their third year of study, and it also serves as a self-study for students and engineers interested in the field. It emphasizes the fundamental phenomena of aerothermodynamics and their governing equations, as well as the simplifying assumptions used when applying these governing equations to solving propulsion-related problems. Derivations of the governing equations from first principles are included, so that students can follow the reasoning and the assumptions made during this process. It is important to include these derivations because if students do not understand how these equations were derived, it is quite probable that they may apply them incorrectly. Furthermore, if students do not understand the reasoning process, they might not be able to apply these principles when solving new problems.

The concepts presented in the book are always followed by examples relevant to propulsion. In this way, the student is exposed to jet engines and rocket engines well before reaching the chapters that describe these engines.

Structure of the Book

The book is split into three parts. Part I presents the basic fluid mechanics and thermodynamics laws and derives the governing equations for different levels of approximation. Part II considers the specific aspects of aerodynamics and thermodynamics that apply to air-breathing engines, and describes and examines the jet engine components. Part III presents a classification of rocket engines and describes the fundamentals of rocket performance.

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Both Part II and Part III rely on the material covered in Part I. Part II and Part III are independent of each other.

Part I begins with a classification of propulsion systems and a brief overview of the history of jet propulsion (Chapter 1). The jet propulsion principle is then introduced using an empirical description. Chapter 2 presents a review of aerothermodynamics. The Reynolds Transport Theorem is used to derive the conservation equations; the thermodynamic laws are established, and their expressions derived for a control volume. In Chapter 3, dimensional and dimensionless reference speeds are introduced, along with a discussion of isentropic and nonisentropic flows. Flows through nozzles are also included. Normal and oblique shock waves are then examined, and solution methods are presented for air and combustion products.

Chapter 4 is concerned with both viscous and thermal boundary layers, and applies them to propulsion problems. Chapter 5 is a brief introduction to combustion. First a classification of fuels is presented, followed by the thermochemical laws. The heats of formation and reaction needed to calculate the adiabatic flame temperature are presented next. It ends with a description of standard fuel.

Part II of the book discusses air-breathing engines. Chapter 6 derives the thrust equation and establishes the engine performance parameters. After introducing the Brayton cycle, the real cycles of the turbojet, turbofan, turboprop, and ramjet engines are analyzed. Chapter 7 presents the jet engine components: inlet diffusers, compressors and fans, combustors, turbines, and exhaust nozzles. The performance of these engine components is then connected to the real cycles covered in Chapter 6. Chapter 8 is devoted to thrust augmentation and such topics as water injection, afterburning, and intraturbine combustion.

Part III concludes with rocket engines and offers in Chapter 9 a classification and succinct presentation of the essential features and general equations related to rocket engines. Chapter 10 presents the performance of chemical rocket engines.

Teaching with this Book

The content of this textbook typically exceeds what can be covered in one semester. The instructor has the option to tailor the material to accommodate a variety of course syllabi based on the specifics of the program at their school.

A large number of examples and problems are included to help the reader understand the concepts and practice the methods introduced in the textbook. The difficulty of the problems varies, so the instructor can tailor homework assignments, tests, and exams accordingly. Solutions are offered to the instructor for all problems. The instructor is also offered web access to several codes that calculate (1) the thermodynamic properties of air and combustion products; (2) normal and oblique shock waves; (3) the Fanno line; (4) the Rayleigh line; (5) adiabatic temperature for different fuels; (6) real cycles analysis for all jet engines; (7) rocket thrust, nozzle exit velocity, and mass flow rate; (8) radial velocity variation in the axial compressor stage; and (9) radial velocity variation in the axial turbine stage.

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Finally, I would like to thank Professors Adrian Bejan and John Slattery, who guided me before and during the genesis of this book. Several chapters of the book were finalized during the summer of 2019 when I visited the DLR Institute of Aeroelasticity in Göttingen, Germany. I am grateful to my host at the institute, Professor Dr. Holger Hennings, and his colleagues, Drs. Virginie Chenaux, Jens Nitzsche, and David Quero Martin, with whom I had numerous interesting technical discussions as well as many relaxing moments. I would also like to express appreciation for the feedback received from my former colleague Dr. Gabriel Marinescu. Last but not least, I am grateful for the suggestions and comments I received from the reviewers of the manuscript.

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Nomenclature

Roman

A	–	Area
A_{cr}	–	Critical area
a	–	Speed of sound
a_0	–	Speed of sound at stagnation temperature
c	–	Chord length or Circumference length
a_{cr}	–	Critical speed of sound
C_f	–	Skin friction drag coefficient
c_p	–	Specific heat at constant pressure
c_v	–	Specific heat at constant volume
E	–	Energy
e	–	Specific energy per unit mass
F	–	Impulse function
$\vec{F}_{\mathcal{V}}$	–	Body force
$\vec{F}_e$	–	External force
$\vec{F}_i$	–	Inertia force
$\vec{F}_p$	–	Pressure force
$\vec{F}_{\mathcal{S}}$	–	Surface force
$\vec{F}_{vis}$	–	Viscous force
F_{cr}	–	Critical impulse function
$\vec{f}$	–	External force per unit mass
f	–	Fuel-air mass ratio
g	–	Gravitational acceleration
H	–	Shape factor
h	–	Enthalpy
h_0	–	Stagnation enthalpy
$\vec{I}$	–	Linear momentum
I	–	Rothalpy or Impulse
$\vec{K}$	–	Angular momentum
$\mathcal{M}$	–	Molecular mass
M	–	Mach number
$\vec{M}_{F_{\mathcal{V}}}$	–	Momentum due to body forces
$\vec{M}_{F_{\mathcal{S}}}$	–	Momentum due to surface forces
m	–	Mass
$\dot{m}$	–	Mass flow rate

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n	–	Number of degrees of freedom of the molecule
$\hat{n}$	–	Normal unit vector
$\mathcal{P}$	–	Power
$\mathcal{P}_{\text{shaft}}$	–	Shaft power
$\mathcal{P}_{\text{shear}}$	–	Shear power
p	–	Static pressure
p_0	–	Stagnation pressure
Pr	–	Prandtl number
Q	–	Heat transfer
$\dot{Q}$	–	Heat transfer rate
$\mathcal{R}$	–	Universal gas constant
R	–	Gas constant
R'	–	Degree of reaction
$\vec{r}$	–	Point vector
Re	–	Reynolds number
$\mathcal{T}$	–	Thrust
T	–	Static temperature or Thwaites parameter
T_0	–	Stagnation temperature
t	–	Time
S	–	Entropy
s	–	Specific entropy per unit mass
St	–	Stanton number
U	–	Internal energy or Transport velocity
u	–	Specific internal energy per unit mass
u^*	–	Friction velocity, $u^* = \sqrt{\tau_{\text{wall}}/\rho}$
$\mathcal{V}$	–	Volume
$\vec{V}$	–	Velocity
$\vec{V}^*$	–	Control volume velocity
V_{max}	–	Maximum velocity for a given stagnation temperature
v	–	Specific volume per unit mass
W	–	Work transfer or Relative velocity
W_n	–	Work transfer due to normal stresses
w	–	Specific work transfer per unit mass
(x, y, z)	–	Cartesian coordinates
y_1	–	Height of the element adjacent to the airfoil
y^+	–	Non-dimensional number, $y^+ = u^* y_1/\nu$

Greek

α	–	Angle of absolute velocity
β	–	Angle of relative velocity
γ	–	Ratio of specific heats or Stagger angle

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δ^* – Displacement thickness
η_{p} – Propulsion efficiency
η_{th} – Thermal efficiency
θ – Momentum thickness or Turning angle
λ – Mean free path or Lambda number or Boundary layer parameter of Excess air
μ – Dynamic viscosity
ν – Kinematic viscosity
ρ – Density
σ – System surface or Solidity
σ^* – Surface of control volume τ^*
τ – System volume
τ^* – Control volume
τ_{wall} – Shear stress at wall
Φ – Equivalence ratio
ϕ – Flow coefficient
Ψ – Work coefficient
ω – Angular velocity

Hebrew

$\aleph$ – Generic variable

Subscripts

0 – Stagnation
1 – Initial or upstream the shock wave
2 – Final or Downstream the shock wave
$-\infty$ – Upstream infinity
a – Atmospheric or Air or Axial component
cr – Critical
cm – Control mass
cv – Control volume
e – Exit
i – Inlet
n – Normal component
stoich – Stoichiometric
t – Tangential component
u – Component in the direction of the transport velocity, U

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