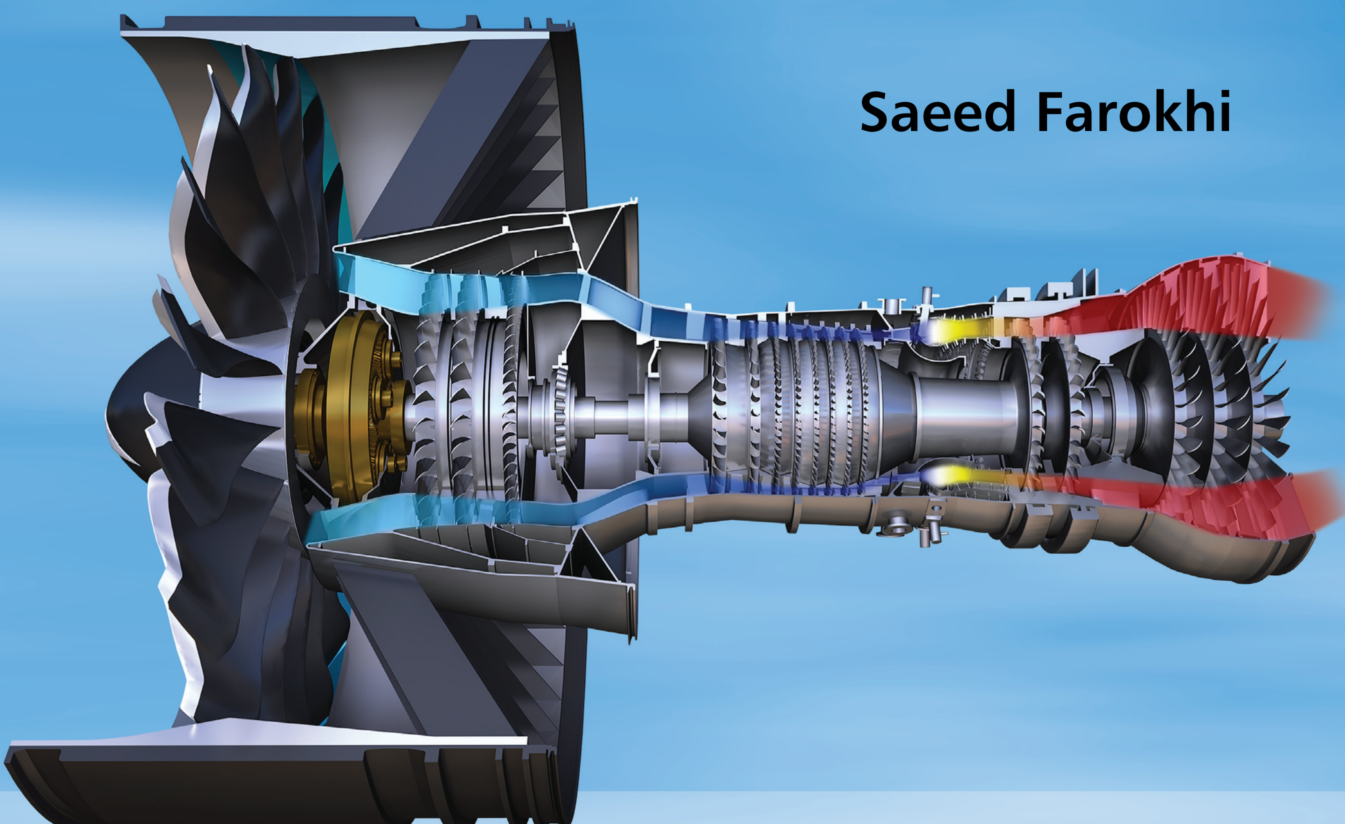
Aircraft Propulsion

Second Edition



Saeed Farokhi

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Second Edition

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WILEY

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I dedicate this book to my lovely grandchildren:

Sophia
Sasha
Sydney
Melody

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Preface to the Second Edition

Since the first edition of this book appeared in 2008, the Uninhabited Aerial Vehicle (UAV) has gained wider interest and market share in aircraft industry. As a result, the second edition has a new chapter dedicated to ***General Aviation and UAV Propulsion Systems***. The remaining changes to the second edition stem from technological advances in propulsion in recent years. For example in the commercial transport sector, we have witnessed the development of ***Ultra-High Bypass (UHB)*** turbofan engines with bypass ratio above 12. An enabling technology to UHB is the ***Geared Turbofan***, which has also received an introductory coverage in the second edition. Other technological advances include ***Chevron Nozzle, Alternative "drop-in" Jet Fuels*** (AJF) and ***advanced heat exchanger in airbreathing rocket engine*** for single-stage-to-orbit application, which are introduced in the new edition.

Some of the reviewers and readers suggested an introductory presentation on ***propeller theory*** could well be integrated with the presentation of the turboprop engines. In response, I have added a section on propeller theory prior to the turboprop cycle analysis section. The instructors often wrote and asked for ***more problems*** at the end of chapters and as a result the new edition has about 50% more end-of-chapter problems than the first edition (i.e., 446 in 2E vs. 305 in 1E). There is an increased interest in Aerospace Engineering (AE) programs to offer propulsion system design as one of the capstone design options in AE curriculum. Towards that goal, additional ***design guidelines*** are added to each component chapter in 2E. A new section on aircraft engines ***performance testing and basic instrumentation*** in ground facilities is added to Chapter 11: Aircraft Engine Component Matching and Off-Design Analysis.

Two new appendices are created in the second edition. The first one is an assembly of 45 ***Ten-Minute Quizzes*** that I had given to my propulsion students at KU in the past three decades. These 10-minute closed books/notes quizzes were given to students at the beginning of my class and concentrated on recent materials. The goal is to show the importance of fundamental concepts, governing laws, important definitions to students and hopefully develop an engineering sense for "ballpark" numbers in propulsion system engineering. The quizzes may be used as an assessment tool by the instructors or the learners themselves. To help the students with the ***"Rules of Thumb" and Trends*** in aircraft propulsion, a second new appendix is created. Students of propulsion and practicing system engineers should find the new appendix on “Rules of Thumb” and Trends particularly useful.

Acknowledgments

I express my sincere appreciation to my friend and colleague at KU-Aerospace, Professor Ray Taghavi, who wrote the invited chapter on General Aviation and UAV Propulsion in the second edition. I received extensive support from Pratt & Whitney on engine data, many engine cutaways, including their new geared turbofan engine, PW1000G, and others. For these, I express my sincere appreciation to Dr. Alan Epstein, Vice President of Engineering Technology and Environment at P&W and Mr. Steve O’Flarity who helped immensely with data and approvals’ gathering at P&W. The copyright permissions from GE Aviation, Boeing and other industry help enrich the presentation and content of this book and are greatly appreciated.

To many colleagues who had adopted my book and sent corrections and helpful suggestions, I express my heartfelt appreciation. I have tried to adopt their suggestions and numerous corrections in the second edition. Since the last edition, I have been assisted by my new doctoral students, Seung-Jae Hwang (2011), Leslie Smith, Amool Raina and Dhaval Mysore who continue to improve my understanding of the advanced concepts in aircraft propulsion and (green) power generation. I am also indebted to many graduate students in the MS level who have helped me in research and provided solutions to the end-of-chapter problems that appear in the solution manual, as an instructor resource.

Finally, my wife Mariam and our growing family continue to be the real inspiration behind this work and I owe my peace of mind and productivity to their love and support.

Saeed Farokhi
Lawrence, Kansas
November 12, 2013

Preface

Intended Audience

This book is intended to provide a foundation for the analysis and design of aircraft engines. The target audience for this book is upper classmen, undergraduates, and first-year graduate students in aerospace and mechanical engineering. The practicing engineers in the gas turbine and aircraft industry will also benefit from the integration and system discussions in the book. Background in thermodynamics and fluid mechanics at a fundamental level is assumed.

Motivation

In teaching under graduate and graduate propulsion courses for the past 23 years, I accumulated supplemental notes on topics that were not covered in most of our adopted textbooks. The supplemental materials ranged from issues related to the propulsion system integration into aircraft to the technological advances that were spawned by research centers around the world. I could have continued handing out supplemental materials to the textbooks to my classes, except that I learned that the presentation style to undergraduate students had to be (peda-gogically) different than for the graduate students. For example, leaving out many steps in derivations of engineering principles can lead to confusion for most undergraduate students. Although it is more important to grasp the underlying principles than the mechanics of some derivations, but if we lose the students in the derivation phase, they may lose sight of the underlying principles as well. Another motivation for attention to details in analysis is my conviction that going back to basics and showing how the end results are obtained demystifies the subject and promotes students' confidence in their own abilities.

Mathematical Level

The mathematics in the present book is intentionally kept at the calculus and basic differential equations level, which makes the book readily accessible to undergraduate engineering students. Physical interpretations of mathematical relations are always offered in the text to help students grasp the physics that is hidden and inherent in the formulas.

This approach will take the mystery out of formulas and let engineering students go beyond symbols and into understanding concepts.

Chapter Organization and Topical Coverage

The first chapter is an introduction to airbreathing aircraft engines and is divided in two parts. The first part reviews the history of gas turbine engine development, and the second part highlights modern concepts in aircraft engine and vehicle design. Young engineering students are excited to learn about the new opportunities and directions in aircraft engine design that are afforded by advances in materials, manufacturing, cooling technology, computational methods, sensors, actuators, and controls. Renewed interest in hypersonicair breathing engines in general and supersonic combustion ramjets in particular as well as a sprawling interest in Uninhabited Aerial Vehicles (UAVs) has revitalized the ever-popular X-planes. The goal of Chapter 1 is first to inform students about the history, but more importantly to excite them about the future of aerospace engineering.

Chapter 2 is a review of compressible flow with heat and friction. The conservation principles are reviewed and then applied to normal and oblique shocks, conical shocks, and expansion waves, quasi-one-dimensional flows in ducts as well as Rayleigh and Fanno flows. At the closing of Chapter 2, the impulse concept and its application to gas turbine engine components are introduced.

Chapter 3 is on engine thrust and performance parameters. Here, we introduce internal and external performance of aircraft engines and their installation effect.

Chapter 4 describes aircraft gas turbine engine cycles. The real and ideal behaviors of engine components are described simultaneously in this chapter. Efficiencies, losses, and figures of merit are defined both physically and mathematically for each engine component in Chapter 4. Once we define the real behavior of all components in a cycle, we then proceed to calculate engine performance parameters, such as specific thrust, specific fuel consumption and thermal and propulsive efficiencies. The ideal cycle thus becomes a special case of a real cycle when all of its component efficiencies are equal to one.

The next five chapters treat aircraft engine components. Chapter 5 deals with aircraft inlets and nozzles. Although the emphasis throughout the book is on internal performance of engine components, the impact of external or installation effects is always presented for a balanced view on aircraft propulsion. As a building block of aircraft inlet aerodynamics, we have thoroughly reviewed two-dimensional and conical diffuser performance. Some design guidelines, both internal and external to inlet cowl, are presented. Transition duct aero-dynamics also plays an important role in design and understanding of aircraft inlets and is thus included in the treatment. Supersonic and hypersonic inlets with their attendant shock losses, boundary layer management, and instabilities such as buzz and starting problem are included in the inlet section of Chapter 5. The study of aircraft exhaust systems comprises the latter part of Chapter 5. Besides figures of merit, the performance of a convergent nozzle is compared with the de Laval or a convergent–divergent nozzle. The requirements of reverse-and vector thrust are studied in the context of thrust reversers and modern thrust vectoring nozzles. In the hypersonic limit, the exhaust nozzle is fully integrated with the vehicle and introductory design concepts and off-design issues are presented. Nozzle cooling is introduced for high-performance military aircraft engine exhaust systems and the attendant performance penalties and limitations are considered.

Plug nozzle and its on-and off-design performances are introduced. Since mixers are an integral part of long-duct turbo fan engines, their effect on gross thrust enhancement is formulated and presented in the nozzle section in Chapter 5.

Chemical reaction is studied on a fundamental basis in Chapter 6. The principles of chemical equilibrium and kinetics are used to calculate the composition of the products of combustion in a chemical reaction. These principles allow the calculation of flame temperature and pollutant formations that drive the design of modern aircraft gas turbine combustors. Further details of flame speed, stability, and flame holding are presented in the context of combustion chamber and afterburner design. Pollutant formation and its harmful impact on ozone layer as well as the greenhouse gases in the exhaust are presented to give students an appreciation for the design issues in modern combustors. Aviation fuels and their properties and a brief discussion of combustion instability known as screech are included in Chapter 6.

Turbomachinery is introduced in three chapters. Chapter 7 deals with axial-flow com-pressors in two and three dimensions. The aerodynamics of axial-flow compressors and stage performance parameters are derived. The role of cascade data in two-dimensional design is presented. Emphasis throughout this chapter is in describing the physical phenomena that lead to losses in compressors. Shock losses and transonic fans are introduced. The physics of compressor instability in stall and surge is described. A simple model by Greitzer that teaches the value of characteristic timescales and their relation to compressor instability is outlined. Chapter 8 discusses the aerodynamics and performance of centrifugal compressors. Distinctive characters of centrifugal compressors are highlighted and compared with axial-flow compressors. Turbine aerodynamics and cooling are presented in Chapter 9. Component matching and engine parametric study is discussed in Chapter 10. Finally, chemical rocket and hypersonic propulsion is presented in Chapter 11.

Instructor Resources

The following resources are available to instructors who adopt this book for their course. Please visit the website at www.wiley.com/go/farokhi to request a password and access these resources.

- Solutions Manual
- Image Gallery

Acknowledgments

I express my sincere appreciation and gratitude to all those who have contributed to my understanding of fluid mechanics and propulsion. Notable among these are my professors in Illinois and MIT. Hermann Krier, Jack Kerrebrock, James McCune, William Hawthorne, and Ed Greitzer contributed the most. The fellow graduate students in the Gas Turbine Lab were also instrumental in my education. Choon Tan, Maher El-Masri, Alan Epstein, Arun Sehra, Mohammad Durali, Wai Cheng, Segun Adebayo, James Fabunmi, and Anthony Nebo discussed their dissertations with me and helped me understand my own. In the Gas Turbine Division of Brown, Boveri and Co. in Baden, Switzerland, I learned the value of hardware engineering and testing, advanced product development, and component research. My colleagues, Meinhard Schobeiri, Konrad Voegeler, Hans Jakob Graf, Peter Boenzli, and Horst Stoff, helped me understand how industry works and how it engineers new products. At the University of Kansas, my graduate students were my partners in research and we jointly advanced our understanding of fluid mechanics and propulsion. My doctoral students, Ray Taghavi, Gary Cheng, Charley Wu, Ron Barrett, and Kyle Wetzel, taught me the most. I appreciate the contributions of 30 M.S. students whom I chaired their theses to our ongoing research. The colleagues at NASA-Lewis (now Glenn) who sponsored my research and provided insightful discussions and hospitality over the summer months in Cleveland are Ed Rice, Khairul Zaman, Ganesh Raman, Bernie Anderson, Reda Mankbadi, James Scott, and Charlie Towne who welcomed me into their laboratory (and their homes), and we enjoyed some fruitful research together. The faculty and staff in the Aerospace Engineering Department of the University of Kansas have been very supportive for the past 23 years, and I would like to express my sincere appreciation to all of them. Vince Muirhead, Jan Roskam, Eddie Lan, Dave Downing, Howard Smith, Dave Ellis, Tae Lim, John Ogg, James Locke, Mark Ewing, Rick Hale, and Trevor Sorenson taught me an appreciation for their disciplines in aerospace engineering. I joined my colleagues in GE-Aircraft Engines in teaching propulsion system design and integration short courses to engineers in industry, FAA, and NASA for many years. I learned from Don Dusa and Jim Younghans from GE and Bill Schweikhard of KSR some intricate aspects of propulsion engineering and flight-testing.

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Saeed Farokhi
Lawrence, Kansas
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Nomenclature

Latin	Definition	Unit
a	Local speed of sound	m/s, ft/s
a	Semimajor axis of inlet elliptic lip (internal)	m, ft
a	Swirl profile parameter	—
a_t	Speed sound based on total temperature	m/s, ft/s
A	Area	m^2, ft^2
A_n	Projection of area in the normal direction	m^2, ft^2
A_9	Nozzle exit flow area	m^2, ft^2
A_{ref}	Reference area	m^2, ft^2
A_o	Inlet (freestream) capture area	m^2, ft^2
A_1	Inlet capture area	m^2, ft^2
A_8, A_{8geo}	Nozzle throat area (geometrical area)	m^2, ft^2
A_{8eff}	Effective nozzle throat area	m^2, ft^2
A_B	Blocked area (due to boundary layer)	m^2, ft^2
A_b	Burning area of grain in solid rocket motors	m^2, ft^2
A_E	Effective area	m^2, ft^2
A_{HL}	Inlet highlight area	m^2, ft^2
A_M	Maximum nacelle area	m^2, ft^2
A_{th}	Inlet throat area	m^2, ft^2
A^*	Sonic throat, choked area	m^2, ft^2
b	Semiminor axis of inlet elliptic lip (internal)	m, ft
b	Swirl profile parameter	—
B	Blockage	—
B	Compressor instability parameter due to Greitzer	—
$\vec{C}$	Absolute velocity vector in turbomachinery	m/s, ft/s
C	Absolute flow speed, i.e., $\sqrt{C_r^2 + C_\theta^2 + C_z^2}$	m/s, ft/s
c	Chord length	m, ft
c	Effective exhaust velocity in rockets	m/s, ft/s
c^*	Characteristic velocity in rockets	m/s, ft/s
C_r, C_θ, C_z	Radial, tangential, axial velocity components in the absolute frame of reference	m/s, ft/s
C_D	drag coefficient, discharge coefficient	—
C_f	Friction drag coefficient	—

c_f	Local skin friction coefficient	—
C_{F}	Force coefficient	—
C_{P}	Pressure coefficient	—
C_{PR}	Diffuser static pressure recovery coefficient	—
C_{A}	Nozzle flow angularity loss coefficient	—
C_{D8}	Nozzle (throat) discharge coefficient	—
C_{fg}	Nozzle gross thrust coefficient	—
C_V	Nozzle exit velocity coefficient	—
C_d	Sectional profile drag coefficient	—
$C_{\mathrm{D}i}$	Induced drag coefficient	—
C_l	Sectional lift coefficient	—
C_h	Enthalpy-equivalent of the static pressure rise coefficient due to Koch	—
c_p	Specific heat at constant pressure	$\mathrm{J/kg \cdot K}$
c_v	Specific heat at constant volume	$\mathrm{J/kg \cdot K}$
$\bar{c}_p$	Molar specific heat at constant pressure	$\mathrm{J/kmol \cdot K}$
d	Flameholder width	m, ft
D	Diameter, drag	m, N
D	Liquid fuel droplet diameter	micron
$D_{\mathrm{flameholder}}$	Flameholder drag	N, lbf
D_{add}	Additive drag	N, lbf
D_{nacelle}	Nacelle drag	N, lbf
D_{pylon}	Pylon drag	N, lbf
D_{r}	Ram drag	N, lbf
D_{spillage}	Spillage drag	N, lbf
$D_{\mathrm{aft\text{-}end}}$	Nozzle aft-end drag	N, lbf
D_{boattail}	Nozzle boattail drag	N, lbf
$D_{\mathrm{plug\text{-}friction}}$	Friction drag on the plug nozzle	N, lbf
D	Diffusion factor in turbomachinery	—
D'	Two-dimensional or sectional profile drag	N/m
$\hat{e}$	Unit vector	—
e	Specific internal energy	J/kg
e_{c}, e_{t}	Polytropic efficiency of compressor or turbine	—
E	Internal energy	J
E_{a}	Activation energy	kcal/mol
f	Fuel-to-air ratio	—
f_{stoich}	Stoichiometric fuel-to-air ratio	—
F_{g}	Gross thrust	N, lbf
F_{lip}	Lip suction force	N, lbf
F_{plug}	Axial force on the nozzle plug	N, lbf
F_{n}	Net thrust	N, lbf
F	Force	N, lbf
F_θ, F_z	Tangential force, axial force	N, lbf
f_{D}	D'Arcy (pipe) friction factor	—
g	Staggered spacing (s.cos β in a rotor and s.cos α in a stator)	m
g_0	Gravitational acceleration on the surface of the earth	$\mathrm{m/s^2}$, $\mathrm{ft/s^2}$
h	Specific enthalpy	J/kg
h_{t}	Specific total enthalpy	J/kg

h	Heat transfer rate per unit area per unit temp. difference	W/m^2K
h	Altitude above a planet	km, kft
h_t	Specific total (or stagnation) enthalpy in the absolute frame; $h + C^2/2$	J/kg
h_{tr}	Specific total enthalpy in relative frame of reference; $h + W^2/2$	J/kg
h_{lg}	Latent heat of vaporization	J/kg
HHV	Higher heating value	J/kg, BTU/lbm
H	Enthalpy	J, ft-lbf
H	Afterburner duct height	m, ft
i	Blade section incidence angle	deg
i_{opt}	Optimum incidence angle	deg
I_s	Specific impulse	s
I_t	Total impulse	$N \cdot s$, $lbf \cdot s$
I	Impulse	N, lbf
K_p	Equilibrium constant based on partial pressure	$(bar)^x$
K_n	Equilibrium constant based on molar concentration	—
L	Length	m, ft
L	Lift	N, lbf
L	Flameholder length of recirculation zone	m, ft
L	Diffuser wall length	m, ft
L	Diffusion length scale in a blade row	m, ft
LHV	Lower heating value	J/kg, BTU/lbm
L/D	Aircraft lift-to-drag ratio	—
M_b	Blowing parameter in film cooling, $\rho_c u_c / \rho_g u_g$	—
M_T	Blade tangential Mach number U/a	—
M_z	Axial Mach number, C_z/a	—
M_r	Relative Mach number (in turbomachinery); $(M_z^2 + M_T^2)^{1/2}$	—
M	Mach number	—
M^*	Characteristic Mach number	—
M_s	Gas Mach number upstream of a shock inside a nozzle	—
m	Parameter in Carter's rule for deviation angle	—
m	Mass	kg, lbm
$\dot{m}$	Mass flow rate	kg/s, lbm/s
$\dot{m}_c$	Corrected mass flow rate	kg/s, lbm/s
$\dot{m}_0$	Air mass flow rate	kg/s, lbm/s
$\dot{m}_f$	Fuel mass flow rate	kg/s, lbm/s
$\dot{m}_p$	Propellant (oxidizer and fuel) mass flow rate	kg/s, lbm/s
$\dot{m}_s$	Mass flow rate through the side of the control volume	kg/s, lbm/s
$\dot{m}_c$	Coolant flow rate	kg/s, lbm/s
MW	Molecular weight	kg/kmol
n	Exponent of superellipse	—
n	Polytropic exponent; parameter in general swirl distribution	—
N	Number of blades; shaft rotational frequency; number of stages	—
N	Number of bluff bodies in a flameholder	—
N	Diffuser axial length	m, ft
N_a	Avagadro's number (6.023×10^{23} molecules per gmole)	—
N_B	Inlet lip bluntness parameter	—
N_c	Corrected shaft speed	rad/s, rpm

$\hat{n}$	Unit normal vector (pointing out of a surface)	—
Nu	Nusselt number	—
Pr	Prandtl number	—
p	Static pressure	bar, Pa, psia
p_t	Total pressure	bar, Pa, psia
p_s	Static pressure upstream of a shock (in nozzle)	bar, Pa, psia
$\wp$	Power	W, hp
$\wp_s$	Shaft power	W, BTU/s
PF	Pattern factor	—
P_f	Profile factor	—
Q	Heat exchange	J, BTU
q	Dynamic pressure	bar, atm
q	Heat transfer rate per unit area (heat flux)	W/m^2, $BTU/s.ft^2$
q	Heat transfer rate per unit mass flow rate	J/kg, BTU/lbm
Q_R	Fuel heating value	kJ/kg, BTU/lbm
$\dot{Q}$	Heat transfer rate	W, BTU/s
$\mathfrak{R}$	Aircraft range	nm
Re	Reynolds number	—
R	Gas constant	J/kg · K, BTU/lbm-°R
$R_{l.e.}$	Blade leading-edge radius	m, in
$\bar{R}$	Universal gas constant	J/kmol · K
r	Mixture ratio (oxidizer to fuel) in liquid propellant rockets	—
r	Burning rate in solid propellant rockets	cm/s, in/s
r	Radius	m, ft
r	Cylindrical or spherical coordinate	—
r_h	Hub radius	m, ft
r_t	Tip radius	m, ft
r_m	Pitchline or mean radius $(r_h+r_t)/2$	m, ft
$°R$	Stage degree of reaction in turbomachinery	—
S	Entropy	J/K
S_L	Laminar flame speed	m/s, ft/s
S_T	Turbulent flame speed	m/s, ft/s
St	Stanton number	—
SN	Smoke number	—
s	Specific entropy	J/kg · K
s	Blade spacing	m, ft
t	Blade thickness	m, ft
t	Time	s, hr
t_{max}	Maximum blade thickness	m, ft
$t_{reaction}$	Reaction time scale in a combustor	ms
t_i	Ignition delay time	ms
t_e	Evaporation time scale in a combustor	ms
T	Static temperature	K, °R, °C, °F
T_t	Total temperature	K, °R, °C, °F
T_f	Reference temperature, 298.16 K	K, °R, °C, °F
T_g	Gas temperature	K, °R, °C, °F
T_c	Coolant temperature	K, °R, °C, °F

T_{af}	Adiabatic flame temperature	K, °R, °C, °F
T_{aw}	Adiabatic wall temperature	K, °R, °C, °F
Tu	Turbulence intensity, $[(u'^2 + v'^2 + w'^2)/3]^{1/2}/V_m$	—
u	Speed, velocity normal to a shock	m/s, ft/s
u	Gas speed	m/s, ft/s
u'_{rms}	Turbulent fluctuating speed (root mean square)	m/s, ft/s
$\vec{U}$	Rotational velocity vector of rotor; v-reg	m/s, ft/s
U_T	Blade tip rotational speed, ωr_t	m/s, ft/s
u', v', w'	Root mean square of fluctuating velocities in 3 spatial directions	m/s, ft/s
$\bar{v}$	Average gas speed in the mixing layer	m/s, ft/s
V	Volume	m^3, ft^3
V	Speed	m/s, ft/s
V_m	Mean speed (used in stall margin or turbulence intensity)	m/s, ft/s
V'	Relative speed used in the stall margin analysis	m/s, ft/s
V_c	Compressor or chamber volume	m^3, ft^3
V_p	Plenum volume	m^3, ft^3
W	Weight	N, lbf
W	Flame width in afterburner	m, ft
W	Width	m, ft
$\vec{W}$, W	Relative velocity vector, relative flow speed	m/s, ft/s
W_r, W_θ, W_z	Radial, tangential and axial velocity components in relative frame of reference	m/s, ft/s
w_c	Rotor specific work (rotor power per unit mass flow rate; $\wp/\dot{m}$)	J/kg, BTU/lbm
w	Specific work	J/kg, BTU/lbm
w	Tangential speed to an oblique shock	m/s, ft/s
w_p	Propellant weight	N, lbf
$W_{visc.}$	Rate of work done by the viscous force	W, BTU/s
X	Solid flow fraction in a rocket nozzle	—
X	Semimajor axis of an elliptic external cowl	m, ft
Y	Semiminor axis of an elliptic external cowl	m, ft
z	Axial coordinate in the cylindrical coordinate system	—
z	Airfoil camber	m, ft
z_{max}	Maximum airfoil camber	m, ft
x, y, z	Cartesian coordinates	—

Greek	**Definition**	**Unit**
α	Bypass ratio in a turbofan engine	—
α	Angle of attack	deg
α	Absolute flow angle with respect to the axial direction in turbomachinery	deg
$\Delta\alpha$	Flow turning angle across a stator blade section	deg
Δp	Pressure drop	Pa, psi
β	Plane oblique shock wave angle	deg
β	Relative flow angle with respect to the axial direction in turbomachinery	deg
β_m	Mean flow angle corresponding to an average swirl across a blade row	deg
$\Delta\beta$	Flow turning angle across a rotor blade section	deg
δ	Boundary layer thickness	m, ft
δ^*	Boundary layer displacement thickness	m, ft
δ	Ratio of total pressure to reference (standard sea level) pressure; p/p_{ref}	—

δ_T	Thermal boundary layer thickness	m, ft
δ^*	Deviation angle defined at the blade trailing edge, a cascade parameter	deg
$\Delta\bar{h}_f^0$	(Standard) molar heat of formation	J/kmol
Δh_f^0	(Standard) specific heat of formation	J/kg
ε	Tip clearance; slip factor in turbomachinery	—
ε	A small quantity ($\ll 1$)	—
ε_g	Emissivity of gas	—
κ	Coefficient of thermal conductivity	$W/m \cdot K$
κ_1	Blade leading-edge angle in turbomachinery	deg
κ_2	Blade trailing-edge angle in turbomachinery	deg
π	Total pressure ratio	—
ω	Angular speed	rad / s, rpm
ϖ	Total pressure loss parameter in a cascade; $\Delta p_t/q_r$	—
ϕ	Spherical coordinate	—
ϕ	Equivalence ratio	—
ϕ	Diffuser wall divergence angle	deg
ϕ	Flow coefficient; C_z/U	—
φ	Camber angle, $\kappa_1 - \kappa_2$	deg
Φ	Cooling effectiveness parameter	—
γ	Ratio of specific heats	—
Γ	Circulation (of a vortex filament), blade circulation	m^2/s, ft^2/s
$\gamma°$	Cascade stagger angle or blade setting angle	deg
ρ	Fluid density	kg/m^3, lbm/ft^3
μ	Coefficient of viscosity	$N \cdot s/m^2$
μ	Mach angle	degree
ν	Kinematic viscosity $\equiv \mu/\rho$	m^2/s, ft^2/s
ν	Prandtl-Meyer angle	radians, degree
π_c	Compressor total pressure ratio	—
π_b	Burner total pressure ratio	—
π_d	Inlet total pressure recovery	—
π_n	Nozzle total pressure ratio	—
π_K	Temperature sensitivity of chamber pressure in solid rockets	%/K, %/F
Π_M	Mach index $\equiv U_T/a_{t1}$	—
θ	Flow angle, cylindrical or spherical coordinate	deg
θ	Nozzle exit flow angle (from axial direction)	deg
θ	Ratio of total temperature to the reference (standard sea level) temperature; T/T_{ref}	—
θ	Circumferential extent of the inlet spoiled or distortion sector	deg
θ^*	Momentum deficit thickness in the boundary layer	m
σ	Cascade or blade solidity; *c/s*, in turbomachinery	—
σ	Stefan–Boltzmann constant	W/m^2K^4
σ_p	Temperature sensitivity of burning rate in solid propellant grain	%/K, %/F
τ	Shear stress	Pa, lbf/ft^2, psi
τ	Total temperature ratio	—
τ	Characteristic timescale	s
τ_r, τ_s	Rotor torque, stator torque in turbomachinery	$N \cdot m$, ft-lbf
τ_t	Turbine total temperature ratio, T_{t5}/T_{t4}	—
τ_λ	Cycle limit enthalpy ratio, $c_{pt}T_{t4}/c_{pc}T_0$	—
$\tau_{\lambda AB}$	Limit enthalpy ratio with afterburner, $c_{p,AB}T_{t7}/c_{pc}T_0$	—
$\tau_{resident}$	Resident timescale	ms