APPLIED COMBUSTION

Second Edition

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Preface to Second Edition

The second edition of *Applied Combustion* will provide its readers with an expanded and updated version of the earlier edition. I anticipate that this second edition will be a source of valuable information for those whose careers involve efforts to advance applied combustion through activities in academic, industrial, and government programs. The subject matter and presentation may be valuable for use in upper-level undergraduate and graduate education, research and development, as well as professional engineering societies.

Basic precepts found in early chapters have been rearranged so that they are developed progressively and thereby utilized more efficiently in later chapters. In the initial chapters, the fundamentals of combustion thermochemistry are still formulated from general principles of chemistry, physics, and thermodynamics. A variety of subject areas are covered, including the ideal oxidation-reaction equation, fuel heat release rates, and incomplete combustion. An expanded discussion of chemical equilibrium has been provided with an extended discussion on fuel cells. The theory of detonation and thermal explosions, collision theory and chemical reactions, as well as basic flame theory have been relocated in the new edition for better continuity of text. The chapter concerning chemical kinetics of combustion now includes a presentation of the important nitrogen-oxygen reaction system. Characteristics of chemical energy resources, or fuels, such as coal, distillates derived from crude oil, alcohols, syncrudes, bio-gas, natural gas, and hydrogen, are treated in detail in the chapters that follow, including material on environmental topics related to their use. The combustion engine chapters contain added coverage of environmental aspects relating to specific combustion characteristics. A new final applied combustion chapter covers the thermal destruction of particular waste materials generated by modern industrial societies.

My career has been shaped by contributions from numerous individuals and institutions including fellow faculty members at the U.S. Merchant Marine and U.S. Naval Academies and the University of Maryland, as well as members of the Society of Automotive Engineers and American Society of Mechanical Engineers. In addition, I have benefited greatly from interaction with many of the customers, such as organizations within the Department of the Navy, with whom I have worked through Environmental Kinetics Ltd. It was while working with my colleagues in these

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institutions and professional societies that much of the philosophy and specific material for this manuscript evolved. A special debt of gratitude and acknowledgment is due my wife, Doris, for her support throughout my career, and specifically for her work as both editor and typesetter on the manuscript for the second edition.

Eugene L. Keating

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Preface to First Edition

Today's world requires that undergraduate engineering education produce graduates having a broad foundation in technical as well as scientific principles of energy conservation and conversion. In addition, engineers and scientists are now needed who can utilize concepts of physics and chemistry to design, develop, operate, and/or maintain current or future energy-consuming machinery. Many texts and references have been written in specific areas of energy, such as thermodynamics, internal combustion engines, gas turbines, chemical kinetics, and flame theory. Other recent publications have attempted to address, in a single volume, the entire field of current energy conversion engineering, covering topics such as solar, nuclear, geothermal, and wind energy systems. *Applied Combustion* provides its readers with a broad engineering introduction to principles of chemical energy conversion, or combustion, as well as practical applications of those laws to a variety of chemical heat engines.

In the early chapters, fundamentals of combustion are formulated from general principles of chemistry, physics, and thermodynamics. Characteristics of chemical energy resources, or fuels, such as coal, distillates derived from crude oil, alcohols, syncrudes, bio-gas, natural gas, and hydrogen, are treated in detail in the following chapters. The final chapters apply these fundamentals to several combustion engines. Basic precepts found in earlier chapters are arranged so that they are progressively developed and utilized in later chapters.

A variety of subject areas are covered in this book, including the ideal oxidation-reaction equation, fuel heat release rates, chemical equilibrium, incomplete combustion, chemical kinetics, theory of detonation and thermal explosions, as well as basic flame theory. Energy characteristics of equipment utilizing chemical fuels, including boilers, gas turbine combustors, and compression- or spark-ignition internal combustion engines, are reviewed. Example problems illustrate a proper engineering analysis and solution technique as well as important principles relevant to understanding many combustion processes and devices. Emphasis is placed on describing general performance in terms of the concept of fuel–engine compatibility, i.e., fuel consumption rates, pollution characteristics, and various energy conversion efficiency interactions of heat and power machinery.

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Currently, only a few publications are available that provide as wide an engineering science introduction to the general subject of combustion as does this work. The use of dual SI and Engineers' dimensions and units, numerous key examples and exercises at the end of each chapter, as well as numerous appendixes, make this book suitable for use as a text in many engineering programs. In addition, the unique bridge between combustion science and combustion technology, thermochemical engineering data, and design formulation of basic performance relationships found in this work should make it a valuable technical reference for many personal and professional engineering libraries.

I hope that this book will stimulate its readers to pursue further this important field of study. Furthermore, I hope that this material will provide a basic foundation for those whose careers involve efforts in current and related areas of engineering activity through graduate education, research and development, and professional engineering societies. Future requirements and advances in applied combustion may have an even greater impact on the power and propulsion fields of aerospace, chemical, marine, and mechanical engineering than have many breakthroughs of the recent past.

I am indebted to numerous individuals and institutions that have contributed over many years to my career. Special acknowledgment is due to my fellow faculty members at the U.S. Merchant Marine and U.S. Naval Academies, as well as members of the Society of Automotive Engineers. It was while working with my colleagues in these institutions that much of the philosophy and specific material for this manuscript evolved.

Eugene L. Keating

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About the Author

EUGENE L. KEATING, Ph.D., P.E., as founder and vice president of Environmental Kinetics, Ltd., is currently providing proprietary engineering services as an energy and environmental consultant to specific clients involved in a variety of emerging advanced heat/power concepts that are early in commercial development. He has been a consulting engineer to the Environmental Protection Branch of the U.S. Navy, Naval Surface Warfare Center, Carderock Laboratories, Maryland, providing engineering design input to a variety of environmental issues related to advanced shipboard waste disposal technology and diesel engine emissions. He has been an energy and internal combustion engine technology consultant to the David Taylor Ship Research and Development Center, an emergency diesel generator reliability consultant to the nuclear industry, and a design consultant for advanced engine technologies.

Dr. Keating taught in the thermal power program at the U.S. Merchant Marine Academy for two years prior to teaching thermodynamics, heat transfer, and combustion in the Mechanical Engineering Department at the U.S. Naval Academy for 16 years. For over 10 years Dr. Keating taught Heat Transfer at the Whiting School of Engineering Evening Program, Johns Hopkins University, Baltimore, Maryland. He is currently an adjunct faculty member in the Professional Master of Engineering Program at the University of Maryland, College Park. Dr. Keating is the author or coauthor of many journal articles and technical reports and the coauthor of two additional engineering books. He is a fellow of the American Society of Mechanical Engineers and the Society of Automotive Engineers, served on the SAE International Board of Directors 1991–1993, and is a member of the Combustion Institute. Dr. Keating received the BSME degree (1966) from the University of California, Santa Barbara; the MSME degree (1968) from the University of Michigan, Ann Arbor; and the Ph.D. degree (1973) in mechanical engineering from Drexel University, Philadelphia, Pennsylvania.

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Contents

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Nomenclature

a	acceleration, m/sec^2, ft/sec^2
a	specific Hemholtz function, J/kg, Btu/lbm
A	generalized chemical compound, i.e., methane, water, etc.
A	area, m^2, ft^2
A	Arrhenius rate constant prefactor
A	total Hemholtz function, J, Btu
AF	air–fuel ratio
$\bar{a}_f^0$	Hemholtz function of formation, J/kgmole, Btu/lbmole
ΔA_c	Hemholtz function of combustion, kJ/kgmole, Btu/lbmole
ΔA_f	Hemholtz function of formation, kJ/kgmole, Btu/lbmole
ΔA_r	Hemholtz function of reaction, kJ/kgmole, Btu/lbmole
$BMEP$	brake mean effective pressure
c	sonic velocity, m/sec, ft/sec
C_p	constant-pressure specific heat, J/kg·K, Btu/lbm·°R
C_v	constant-volume specific heat, J/kg·K, Btu/lbm·°R
d	diameter, m, ft
D	total differential operator
F	force, N, lbf
FA	fuel–air ratio
g	gravitational acceleration, m/sec^2, ft/sec^2
g_0	dimensional constant, 1.0 kg·m/N·sec^2, 32.1724 lbm/lbf·sec^2
g	Gibbs function, J/kg, Btu/lbm
G	total Gibbs function, J, Btu
G	mass flow per unit area, kg/m^2·sec, lbm/ft^2·sec
ΔG_c	Gibbs function of combustion, kJ/kgmole, Btu/lbmole

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ΔG_f	Gibbs function of formation, kJ/kgmole, Btu/lbmole
ΔG_r	Gibbs function of reaction, kJ/kgmole, Btu/lbmole
h	specific enthalpy, J/kg, Btu/lbm
H	total enthalpy, J, Btu
h_{fg}	latent heat of vaporization, J/kg, Btu/lbm
$\overline{h}_f^0$	molar enthalpy of formation, J/kgmole, Btu/lbmole
HHV	fuel higher heating value, J/kg, Btu/lbm
ΔH_c	heat of combustion, kJ/kgmole, Btu/lbmole
ΔH_f	heat of formation, kJ/kgmole, Btu/lbmole
ΔH_r	heat of reaction, kJ/kgmole, Btu/lbmole
$IMEP$	indicated mean effective pressure, kPa, psi
k	Arrhenius elemental rate constant
$\boldsymbol{k}$	Boltzmann's constant
K_c	equilibrium constant based on species concentrations
K_p	equilibrium constant based on partial pressures
L	length, m, ft
LHV	fuel lower heating value, J, Btu
M	total mass, kg, lbm
m_i	mass of species *i*, kg, lbm
mf_i	mass fraction
MW	molecular weight, kg/kgmole, lbm/lbmole
MEP	mean effective pressure, kPa, lbf
N	number of moles
N	rotational speed, rev/sec
N_m	Mach number
P	pressure, N/m^2 or Pa, lbf/in.^{2}
P_r	relative pressure
q	heat transfer per unit mass, J/kg, Btu/lbm
Q	total heat transfer, J, Btu
R	elementary reaction rate
R	specific gas constant, J/kg·K, Btu/lbm·°R
R_i	reactant species *i*
r_c	cutoff ratio
r_e	expansion ratio
r_p	pressure ratio
r_v	compression ratio
s	specific entropy, J/kg·K, Btu/lbm·°R
S	total entropy, J, Btu
$\overline{s}_f^0$	molar entropy of formation, J/kgmole, Btu/lbmole
ΔS_c	entropy of combustion, kJ/kgmole, Btu/lbmole
ΔS_f	entropy of formation, kJ/kgmole, Btu/lbmole
ΔS_r	entropy of reaction, kJ/kgmole, Btu/lbmole
$S.G.$	specific gravity

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t	time, sec
T	temperature, °C and K, °F and °R
u	specific internal energy, J/kg·K, Btu/lbm·°R
U	total internal energy, J, Btu
$\overline{u}_f^0$	molar internal energy of formation, J/kgmole, Btu/lbmole
ΔU_c	internal energy of combustion, kJ/kgmole, Btu/lbmole
ΔU_f	internal energy of formation, kJ/kgmole, Btu/lbmole
ΔU_r	internal energy of reaction, kJ/kgmole, Btu/lbmole
v	specific volume, m^3/kg, ft^3/lbm
V	total volume, m^3, ft^3
V	velocity, m/sec, ft/sec
V_C	clearance volume, m^3/stroke, ft^3/stroke
V_D	displacement volume, m^3/stroke, ft^3/stroke
w	specific work *m*, J/kg, ft·lbf/lbm
W	total work, J, ft·lbf
W	total weight, N, lbf
$\overline{x}_i$	mole fraction of species *i*
Z	elevation, m, ft
Z_{AB}	collision frequency, number of collisions/sec
δ	differential operator
Δ	finite difference in parameters
γ	specific heat ratio
γ	specific weight, N/m^3, lbf/ft^3
λ	mean free path, cm/collision
η	efficiency (subscript will designate the particular value)
σ	molecular diameter, m^3, ft^3
Σ	summation operator
τ	torque, N·m, ft·lbf
Φ	equivalence ratio
ν	moles of species

Notes on Nomenclature Rules:

A dot over a symbol indicates a derivate with respect to time;

$\dot{Q}$	heat flux, W, Btu/hr
$\dot{W}$	power, W, hp

A bar over a symbol indicates that the parameter is on a mole basis:

$\overline{h}$	molar specific enthalpy, J/kgmole, Btu/lbmole
$\overline{R}$	universal gas constant, J/kgmole·K, Btu/lbmole·°R

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An angle bracket $\langle\quad\rangle$ is an operator that implies that the quantity in question is a function of the parameters contained within:

$C_p\langle T\rangle$ constant specific heat is a function of temperature
$V\langle t\rangle$ velocity is a function of time

Subscript i or j references the quantity of a species i or j:

MW_i
mf_j

An arrow through a term in an equation means that it vanishes in that equation:

$\cancel{dE}$

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