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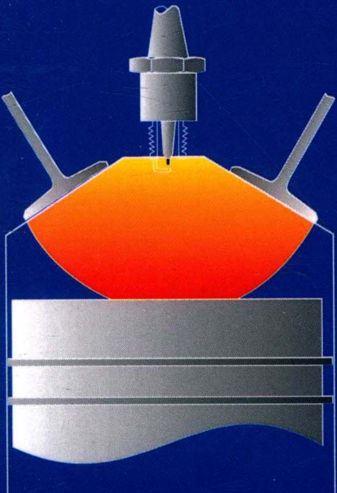
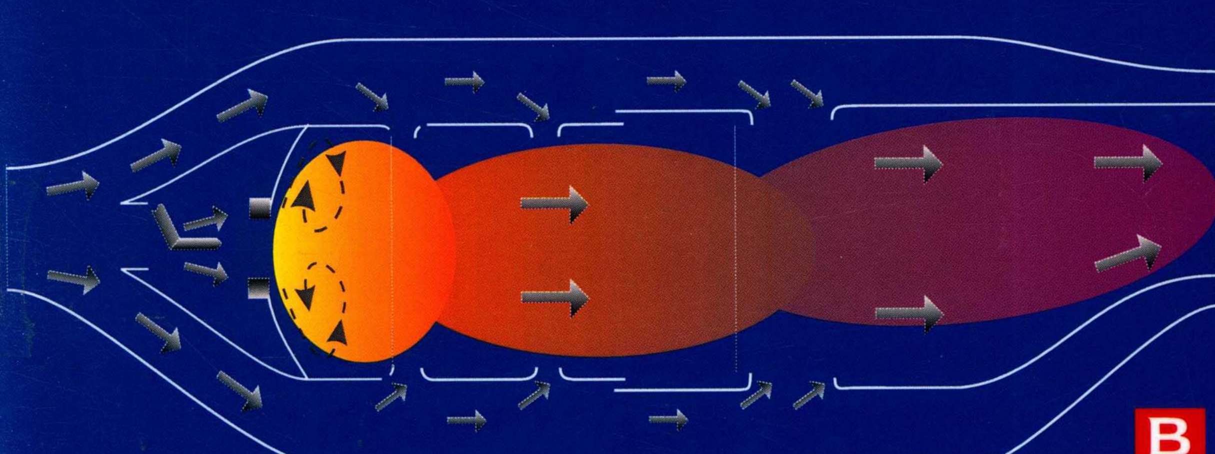


ADVANCED THERMODYNAMICS FOR ENGINEERS

DESMOND E. WINTERBONE and ALI TURAN



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Advanced Thermodynamics for Engineers
Second Edition

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Advanced Thermodynamics for Engineers

Preface – First Edition

When reviewing, or contemplating writing, a text-book on engineering thermodynamics, it is necessary to ask what does this book offer that is not already available? The author has taught thermodynamics to mechanical engineering students, at both undergraduate and postgraduate level, for 25 years, and has found that the existing texts cover very adequately the basic theories of the subject. However, by the final years of a course, and at postgraduate level, the material which is presented is very much influenced by the lecturer, and here it is less easy to find one book which covers all the syllabus in the required manner. This book attempts to answer this need, for the author at least.

The engineer is essentially concerned with manufacturing devices to enable tasks to be performed cost-effectively and efficiently. Engineering has produced a new generation of automatic 'slaves' which enable those in the developed countries to maintain their lifestyle by the consumption of fuels rather than by manual labour. The developing countries still rely to a large extent on 'manpower', but the pace of development is such that the whole world wishes to have the machines and quality of life which we, in the developed countries, take for granted: this is a major challenge to the engineer, and particularly the thermodynamicist. The reason why the thermodynamicist plays a key role in this scenario is because the methods of converting any form of energy into power are the domain of thermodynamics: all of these processes obey the four laws of thermodynamics, and their efficiency is controlled by the second law. The emphasis of the early years of an undergraduate course is on the first law of thermodynamics, which is simply the conservation of energy; the first law does not give any information on the *quality* of the energy. It is the hope of the author that this text will introduce the concept of the quality of energy and help future engineers use our resources more efficiently. Ironically, some of the largest demands for energy may come from cooling (e.g. refrigeration and air-conditioning) as the developing countries in the tropical regions become wealthier – this might require a more basic way of considering energy utilisation than that emphasised in current thermodynamic texts. This book attempts to introduce basic concepts which should apply over the whole range of new technologies covered by engineering thermodynamics. It considers new approaches to cycles, which enable their irreversibility to be taken into account; a detailed study of combustion to show how the chemical energy in a fuel is converted into thermal energy and emissions; an analysis of fuel cells to give an understanding of the direct conversion of chemical energy to electrical power; a detailed study of property relationships to enable more sophisticated analyses to be made of both high and low temperature plant; and irreversible thermodynamics, whose principles might hold a key to new ways of efficiently converting energy to power (e.g. solar energy, fuel cells).

The great advances in the understanding and teaching of thermodynamics came rapidly towards the end of the nineteenth century, and it was not until the 1940s that these were embodied in thermodynamics textbooks for mechanical engineers. Some of the approaches used in teaching thermodynamics still contain the assumptions embodied in the theories of heat engines without explicitly recognising the limitations they impose. It was the desire to remove some of these shortcomings, together with an increasing interest in what limits the efficiency of thermodynamic devices, that led the author down the path which has culminated in this text.

I am still a strong believer in the pedagogical necessity of introducing thermodynamics through the traditional route of the zeroth, first, second and third laws, rather than attempting to use the Single-Axiom Theorem of Hatsopoulos and Keenan, or The Law of Stable Equilibrium of Haywood. While both of these approaches enable thermodynamics to be developed in a logical manner, and limit the reliance on cyclic processes, their understanding benefits from years of experience – the one thing students are lacking. I have structured this book on the conventional method of developing the subject. The other dilemma in developing an advanced level text is whether to introduce a significant amount of *statistical thermodynamics*; since this subject is related to the particulate nature of matter, and most engineers deal with systems far from regions where molecular motion dominates the processes, the majority of the book is based on *equilibrium thermodynamics*; which concentrates on the macroscopic nature of systems. A few examples of statistical thermodynamics are introduced to demonstrate certain forms of behaviour, but a full understanding of the subject is not a requirement of the text.

The book contains XX chapters and while this might seem an excessive number, these are of a size where they can be readily incorporated into a degree course with a modular structure. Many such courses will be based on 2 h lecturing per week, and this means that most of the chapters can be presented in a single week. Worked examples are included in most of the chapters to illustrate the concepts being propounded, and the chapters are followed by exercises. Some of these have been developed from texts which are now not available (e.g. Benson, Haywood) and others are based on examination questions. Solutions are provided for all the questions. The properties of gases have been derived from polynomial coefficients published by Benson: All the parameters quoted have been evaluated by the author using these coefficients, and equations published in the text: this means that all the values are self-consistent, which is not the case in all texts. Some of the combustion questions have been solved using computer programs developed at UMIST, and these are all based on these gas property polynomials. If the reader uses other data, e.g. JANAF tables, the solutions obtained might differ slightly from those quoted.

Engineering thermodynamics is basically *equilibrium thermodynamics* although for the first two years of the conventional undergraduate course these words are used but not often defined. Much of the thermodynamics done in the early years of a course also relies heavily on *reversibility*, without explicit consideration of the effects of irreversibility. Yet, if the performance of thermodynamic devices is to be improved, it is the irreversibility which must be tackled. This book introduces the effects of irreversibility through considerations of availability (exergy), and the concept of the endoreversible engine. The thermal efficiency is related to that of an ideal cycle by the rational efficiency – to demonstrate how closely the performance of an engine approaches that of a reversible one. It is also shown that the Carnot efficiency is a very artificial yardstick against which to compare real engines: the internal and external reversibilities imposed by the cycle mean that it produces zero power at the maximum achievable efficiency. The approach by Curzon and Ahlborn to define the efficiency of an endoreversible engine producing maximum power output is introduced: this shows the effect of *external irreversibility*. This analysis also introduces the concept of *entropy generation* in a manner readily understandable by the engineer; this concept is the cornerstone of the theories of *irreversible thermodynamics* which are at the end of the text.

Whilst the laws of thermodynamics can be developed in isolation from consideration of the property relationships of the system under consideration, it is these relationships which enable the equations to be *closed*. Most undergraduate texts are based on the evaluation of the fluid properties from the simple perfect gas law, or from tables and charts. While this approach enables typical engineering problems to be solved, it does not give much insight into some of the phenomena which can happen under certain circumstances. For example, is the specific heat at constant volume a function of temperature alone for gases in certain regions of the state diagram? Also, why is the assumption of constant stagnation, or even static, temperature valid for flow of a perfect gas through a throttle, but never for steam? An understanding of these effects can be obtained by examination of the more complex equations of state. This immediately enables methods of gas liquefaction to be introduced.

An important area of engineering thermodynamics is the combustion of hydrocarbon fuels. These have formed the driving force for the improvement of living standards which has been seen over the last century, but they are presumably finite, and are producing levels of pollution that are a constant challenge to engineers. At present, there is the threat of global warming due to the build-up of carbon dioxide in the atmosphere: this requires more efficient engines to be produced, or for the carbon/hydrogen ratio in fuels to be reduced. Both of these are major challenges, and while California can legislate for the zero emissions vehicle (ZEV) this might not be a worldwide solution. It is said that the ZEV is an electric car running in Los Angeles on power produced in Arizona! – obviously a case of exporting pollution rather than reducing it. The real challenge is not what is happening in the West, although the energy consumption of the United States is prodigious, but how can the aspirations of the East be met. The combustion technologies developed today will be necessary to enable the newly industrialised countries (NICs) to approach the level of energy consumption which we enjoy. The section on combustion goes further than many general textbooks in an attempt to show the underlying general principles which affect combustion, and it introduces the interaction between thermodynamics and fluid mechanics which is so important to achieving clean and efficient combustion. The final chapter introduces the thermodynamic principles of fuel cells, which enable the direct conversion of the Gibbs energy in the fuel to electrical power. Obviously the fuel cell could be a major contributor to the production of 'clean' energy and is a goal for which it is worth aiming.

Finally, a section is included on irreversible thermodynamics. This is there partly as an intellectual challenge to the reader, but also because it introduces concepts that might gain more importance in assessing the performance of advanced forms of energy conversion. For example, although the fuel cell is basically a device for converting the Gibbs free energy of the reactants into electrical energy, is its efficiency compromised by the thermodynamics of the steady state that are taking place in the cell? Also, will photovoltaic devices be limited by phenomena considered by irreversible thermodynamics?

I have taken the generous advice of Dr Joe Lee, a colleague in the Department of Chemistry, UMIST, and modified some of the wording of the original text to bring it in line with more modern chemical phraseology. I have replaced the titles Gibbs free energy and Helmholtz free energy by Gibbs and Helmholtz energy respectively: this should not cause any problems and is more logical than including the word 'free'. I have bowed, with some reservations, to using the internationally agreed spelling sulfur, which again should not cause problems. Perhaps the most difficult concept for engineers will be the replacement of the terms 'mol' and 'kmol' by the term 'amount of substance'. This has been common practice in chemistry for many years, and separates the general concept of a quantity of matter from the units of that quantity. For example, it is common to talk of a mass of substance without defining whether it is in grams, kilograms, pounds, or whatever system of units is appropriate. The use of the phrase 'amount of substance' has the same generalising effect when dealing with quantities based on molecular equivalences. The term mol will still be retained as the adjective and hence molal enthalpy is the enthalpy per unit amount of substance in the appropriate units (e.g. kJ/mol, kJ/kmol, Btu/lb-mol, etc.).

The author would like to acknowledge all those who have helped and encouraged the writing of this text. First, I would like to acknowledge the influence of all those who attempted to teach me thermodynamics; and then those who encouraged me to teach the subject, in particular Jim Picken, Frank Wallace and Rowland Benson. Second, I would like to thank those who have helped in the production of this book by reading the text or preparing some of the material. Amongst these are Ed Moses, Marcus Davies, Loh, Joe Lee, Richard Pearson and John Horlock; whilst they have read parts of the text and provided their comments, the responsibility for the accuracy of the book lies entirely in my hands. I would also like to acknowledge my secretary, Mrs P Shepherd, who did some of the typing of the original notes. Finally, I must thank my wife, Veronica, for putting up with lack of maintenance in the house and garden, and many evenings spent alone while I concentrated on this work.

Desmond E. Winterbone

Preface – Second Edition

It is almost 20 years since I wrote the first edition of this book, and I asked myself a number of questions when Elsevier invited me to consider writing a second edition. What is the status of thermodynamics in engineering education? Would a new edition basically be a minor update of the original one? Should I invite a 'colleague' to join me as a co-author? The answer to the last question is that Professor Ali Turan, who was appointed to my Chair in UMIST when I retired, agreed to join me in this venture. Professor Turan was extremely enthusiastic about the place of the book in engineering education, and this buoyed up my spirits during the long period of preparing the manuscript.

The first question we tackled was the status of thermodynamics in engineering syllabuses: we both agreed that it should be an integral part of any course, and that its influence and concepts were central to understanding a wide range of subjects. The need for an understanding of thermodynamic principles has increased over the last 20 years as the use of energy has expanded. The increase in the global demand for energy is shown in Figure 1, where it can be seen that a growth of around 3% per annum is occurring, but this is happening mainly in non-OECD countries where more than 5% is happening.

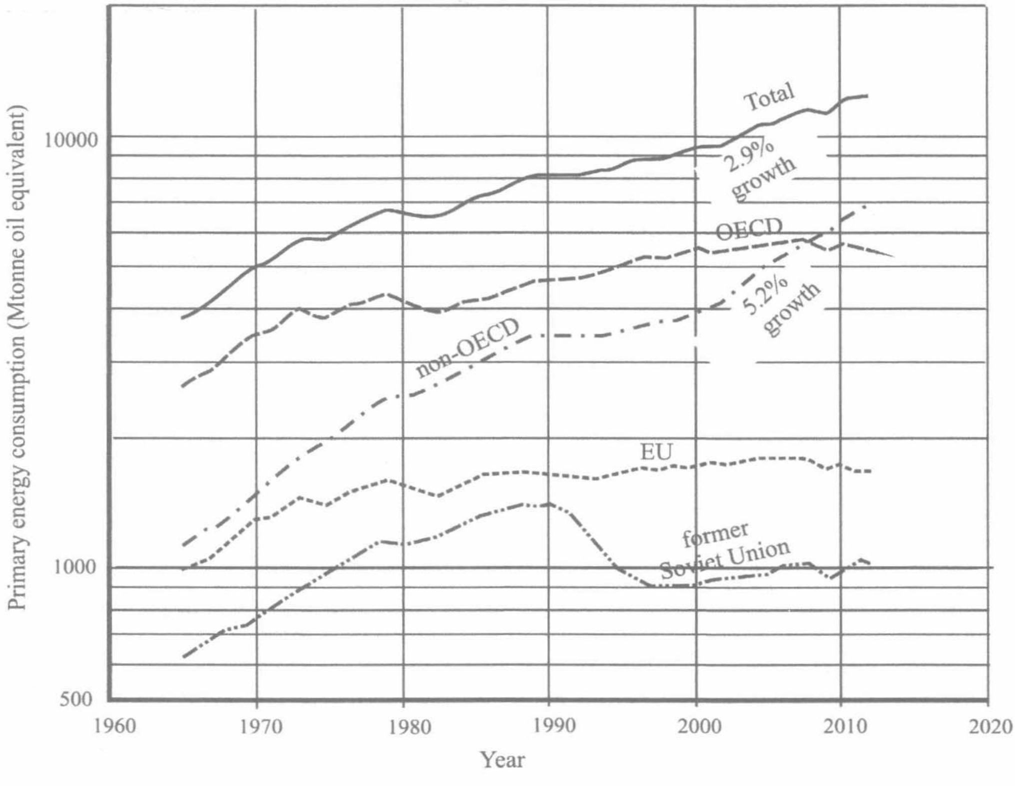


FIGURE 1

Increase in energy use since 1965.

Obviously it would be beneficial if the developed (OECD) countries could reduce their energy consumption, but it is essential that the developing countries are encouraged to employ the most efficient technology to contain their legitimate demands.

We then considered the development of the new edition, and were helped by comments on the first edition obtained by the publishers. We both agreed that the underlying approach, centred on equilibrium thermodynamics, should be maintained, but it was apparent that the original text, written by me to support the final year undergraduate course, and the postgraduate Masters course, relied too heavily on the structure of those courses and the assumed background of the reader. We hope we have remedied this by adding material at the beginning of the book that revises basic thermodynamics – this removes the rapid immersion of the reader in the concepts of equilibrium in the first chapter. We have also added some more 'practical' material on 'heat engine' cycles early in the text to help the reader get a feel for the applications of the more esoteric material later. Finally, Chapters 16 and 17 discuss how the basic concepts of engineering thermodynamics affect the operation of reciprocating internal combustion engines and gas turbines. Professor Turan provided many ideas about the structure of the book, and these are evident if the first and second editions are compared: we hope that the development of the material is now more logical than in the first edition. He was also able to bring in new material in a number of chapters, particularly on finite time thermodynamics, and fuel cells, which has enhanced this edition.

All of these modifications have resulted in a book that now has 21 chapters. Many of the chapters are based on the original 17 of the first edition. In some cases the changes are minor, resulting in the removal of spelling or minor arithmetic errors. In others, new material has been added, or some material has been moved to other more appropriate chapters. All of the original diagrams have received minor modifications, if only to the typeface, and some have been redrawn. The four new chapters cover a range of material. Chapter 1 is basically a revision of early thermodynamics, concentrating mainly on the concepts of systems and the first law: the material should be familiar to most readers. Chapter 2 has been modified to introduce the second law and the concept of the heat engine, before subsuming Chapter 1 of the first edition. Chapter 3 discusses heat engine cycles and shows that all heat engines have an efficiency dominated by a temperature ratio – the definition of this varies with the cycle. This has an important bearing on deciding how to improve the efficiency of a power plant. Realistic reciprocating engine cycles are introduced in the new Chapter 16, and it is shown why such engines do not achieve the efficiency of ideal heat engine cycles. In addition two computer programs are made available, in Chapters 12 and 16, to allow teachers and students to more fully develop the concepts in those chapters. Gas turbine cycles are discussed in some detail in Chapter 17, and these are related to the basic principles introduced in Chapter 2. Almost 90 completely new diagrams are included in this text, and it is hoped these help in the understanding of the principles involved.

I would like to acknowledge the work done by John Nichols and Richard Pearson in developing the two programs available for use with this book. They developed comprehensive programs that I have emasculated to make more amenable for the purposes of this book: I hope these prove useful. I must also thank Philip Kosky who sent me some corrections for the first edition. The authors would also like to acknowledge the contributions made by Khurram Kafeel, Dr Mario Ferrari, Dr Kate Smith, Xiaochuan Yang in preparing this edition. It is thanks to them that many of the errors in the original manuscript have been removed. Any shortcomings that remain in the text must be laid at the authors' oversight, and for these we apologise. We would also like to acknowledge the patience of Chelsea Johnston at Elsevier who has coped with our many e-mails, our late response to requests, and our requirements to achieve the product we all desire.

Finally, I must thank my wife, Veronica, for allowing me to spend much more time on this project than I told her it would take. She has put up with my lack of domestic effort for almost a year, but I am sure there will be much to do now this task is finished.

Desmond E. Winterbone
Marple Bridge, UK
October 2014

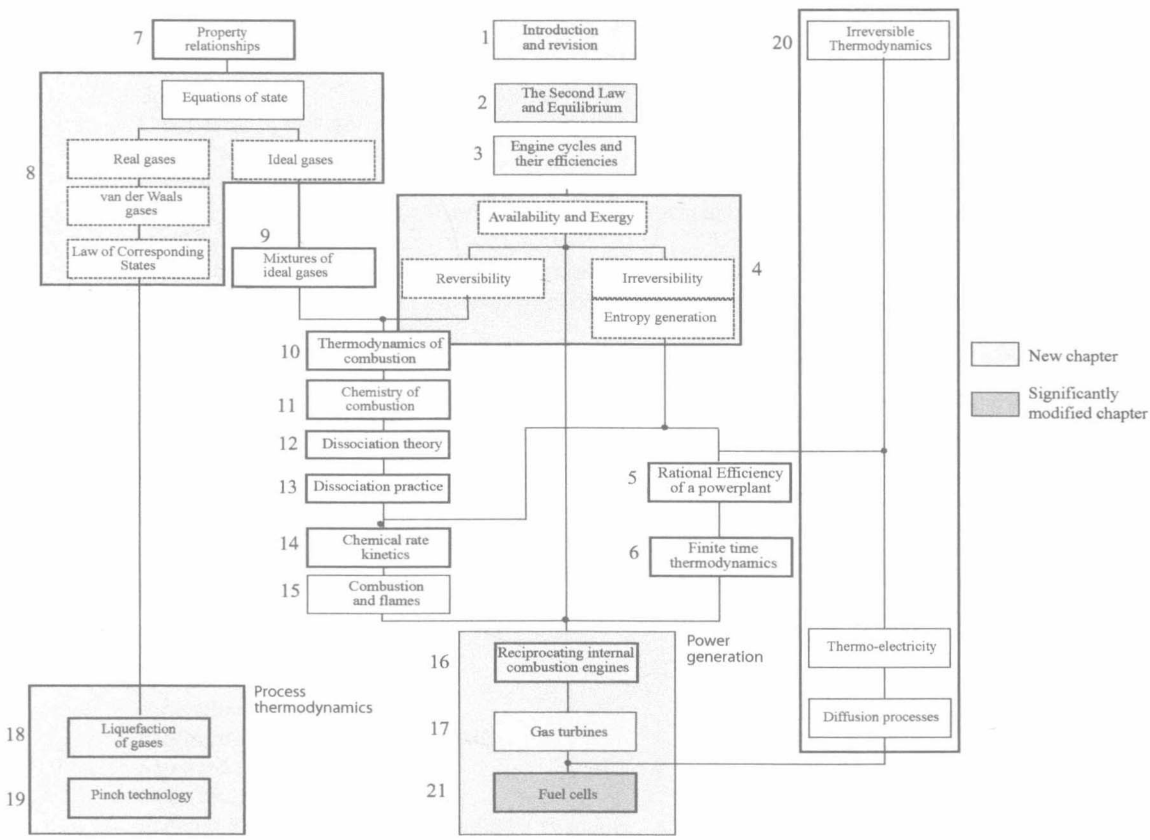
When Professor Winterbone asked me to join him in putting together the second edition of Advanced Thermodynamics for Engineers, I was a bit apprehensive initially, because thermodynamics is regarded as a somewhat "stagnant topic" for an engineering curriculum. However, as the exercise developed and the contents were moulded into what I thought were self-consistent and fairly comprehensive format, I came to appreciate the all unifying power of the subject in terms providing a core competency for an engineer to possess regardless of his/her chosen field of endeavour. In this respect, I was guided tremendously by the long years I had spent in an industrial setting worrying about very down to earth design and development, and hardware issues for a variety of applications. These covered issues ranging from power generation and propulsion issues to chemical processing plant, which also included biophysical and biomedical attributes. I have always been somewhat concerned about the dismissive attitude of the practising engineer with the fundamental, all encompassing, physicochemical framework provided by thermodynamics, while at the same time being equally cognizant of the minimalistic utilitarian focus of the academic environment in contributing to practical solutions that the engineer has to tackle. It is on that basis I have tried to develop a mutually compatible viewpoint in providing contributions to resolve engineering issues i.e. literally, at an interface that tried to set a rigorous academic basis for solving challenging engineering problems that are almost guaranteed to require an intimate and seamless intermeshing of fundamental theory and unique creativity and applications.

Thus, a particular distinguishing feature of the current edition, which hopefully will come across forcefully in relation to this book as distinct from the large number of alternatives available in the literature, is the emphasis it places on industrial utilisation. This is demonstrated in some very practically oriented considerations that thermodynamics provides in the design and development of conversion efficient hardware: this is so important in this day and age. I would like to further stress that, due to my background and philosophy as succinctly summarised above, I have seen a large number of eye-opening examples, of such considerations in industrial settings and the innovative solutions provided by engineers and scientists of old school thermodynamics, which are as relevant today as they were then. It is with that thought that I would like to reader to appreciate the vibrancy of the subject displaying a systematic rational basis for design and development of hardware while being true to the principles laid by the originators of the subject/concepts.

Finally, I would like to thank my wife, Ayse, and my daughter, Melissa, for being a constant source of inspiration during the effort and apologise sincerely for all the absences regarding household chores and helping with take home assignments. Unfortunately, this probably would be the norm rather than the exception as I have committed myself (foolishly) to a whole slew of writing and hope they will forgive me for it.

Ali Turan
Manchester, UK
October 2014

Structure of the Book



Notation

a	Activity coefficient
a	Specific non-flow availability
a	Coefficient in van der Waals equation
a_f	Specific flow availability
a_i	Enthalpy coefficient for gas properties
A	Non-flow availability
A	Area
A	Tafel constant
AFC	Alkaline fuel cell
b	Specific exergy
b	Coefficient in van der Waals equation
b	Bypass ratio
B	Exergy
c_p	Specific heat capacity at constant pressure (sometimes abbreviated to specific heat at constant pressure)
$\tilde{c}_p$	Mean value of specific heat capacity at constant pressure over a range of temperatures
$\bar{c}_p$	Molar specific heat capacity at constant pressure (i.e. specific heat capacity at constant pressure based on *mols*)
c_v	Specific heat capacity at constant volume (sometimes abbreviated to specific heat at constant volume)
$\bar{c}_v$	Molar specific heat capacity at constant volume (i.e. specific heat capacity at constant volume based on *mols*)
C	Conductivity for heat flow into engines
CN	Cetane number
d	Increment in – usually used for definite integral, e.g. property, etc.
D	Mass diffusivity
DMFC	Direct methanol fuel cell
e	Specific internal energy
egr	Exhaust gas recirculation
E	Internal energy
E	Activation energy
E	Electromotive force of a cell (emf)
E^0	Standard emf of a cell
E_{oc}	Open circuit voltage
f	Specific Helmholtz energy (Helmholtz function)
f_f	Flame speed factor
F	Helmholtz energy (Helmholtz function)
F	Force
F	Thrust of gas turbine
F_s	Specific thrust of gas turbine
F	Faraday constant (charge carried by kmol of unit positive valency [96,487 kC/kmol])

g	Specific Gibbs energy (specific Gibbs function)
g_0	Specific Gibbs energy at datum temperature (or absolute zero)
g	Acceleration due to gravity
G	Gibbs energy (Gibbs function)
h	Specific enthalpy
h_0	Specific enthalpy at datum temperature (or absolute zero)
h	Height
H	Enthalpy
I	Irreversibility
i	Electrical current
J	Thermodynamic velocity, or flow
$\tilde{J}$	Joule's mechanical equivalent of heat
J_I	Electrical flow rate
J_Q	Heat flow rate
J_S	Entropy flow rate
k	Isothermal compressibility, isothermal bulk modulus
k	Thermal conductivity
k	Boltzmann constant (1.38062×10^{-23} J/K)
k_s	Adiabatic, or isentropic, compressibility
k	Rate of reaction
K	Karlovitz number $[(u'/\ell_T)(\delta_\ell/u_\ell)]$
K_F	Specific thrust coefficient of nozzle
K_p	Equilibrium constant
$\mathbf{l}$	Length
l_T	Taylor microscale
L	Coefficient relating thermodynamic force and velocity
Le	Lewis number$[\lambda/pc_pD]$
m	Mass
$\dot{m}$	Mass flow rate
m_w	Molecular weight
MCFC	Molten carbonate fuel cell
n	Polytropic index
n	Amount of substance, chemical amount (sometimes referred to as number of moles)
n	Reaction order
N	Engine speed (rev/min)
$\tilde{N}$	Avogadro constant (6.023×10^{26} kmol^{-1})
p	Pressure
$\bar{p}$	Mean effective pressure
p_i	Partial pressure of component i
p_0	Datum pressure (often 1 bar or 1 atm)
P	Preparation rate (Whitehouse and Way equation.)
P	Power output
PAFC	Phosphoric acid fuel cell
PEMFC	Proton exchange membrane fuel cell
P_r	Prandtl number $[c_p\mu/k]$

q	Specific heat (energy) transfer
q_l	Electrical charge
Q	Heat (energy) transfer
Q^*	Heat of transport
Q_p	Enthalpy of reaction (energy of reaction at constant pressure)
Q_p'	Calorific value (at constant pressure) $= -Q_p$
Q_v	Internal energy of reaction (energy of reaction at constant volume)
Q_v'	Calorific value (at constant volume) $= -Q_v$
r	Compression ratio (of reciprocating engine)
r_p	Pressure ratio
r_w	Work ratio
r_{wb}	Back work ratio
R	Specific gas constant
$\mathbf{R}$	Rate of formation, rate of reaction
R	Radical
R	Electrical resistance
R	Reaction rate (Whitehouse and Way eqn.)
$\Re$	Universal gas constant
Re	Reynolds number $[\rho v \ell / \mu]$
s	Specific entropy
s_0	Specific entropy at datum temperature (or absolute zero)
S	Entropy
S^*	Entropy of transport
SOFC	Solid oxide fuel cell
SPFC	Solid polymer fuel cell
t	Temperature on discontinuous scale
t	Time
T	Temperature on absolute scale (thermodynamic temperature)
u	Specific intrinsic internal energy
u_0	Specific intrinsic internal energy at datum temperature (or absolute zero)
u'	Turbulence intensity
$u\mathrm{l}$	Laminar burning velocity
u_{t}	Turbulent burning velocity
U	Intrinsic internal energy
U	Overall heat transfer coefficient
v	Specific volume
V	Volume
V	Velocity
V	Voltage
$\overline{V}_p$	Mean piston speed (for reciprocating engines)
w	Specific work
$\widehat{w}$	*Maximum* specific work
W	Work
x	Dryness fraction (quality)
x	Molar fraction

x	Distance
X	Thermodynamic force
y	Mass fraction
z	Valency

Greek characters

α	Degree of dissociation
α	[A]/[A]e
α	Branching multiplication coefficient
α	Molecular thermal diffusivity
α	Crank angle (in internal combustion engines)
α	Constant volume period in dual combustion cycle
β	Coefficient of thermal expansion
β	Constant pressure period for diesel or dual combustion cycles
β	[B]/[B]e
δ	Increment in – usually used for indefinite integral, e.g. work (W), heat (Q)
δ	[D]/[D]e
ε	Potential difference, voltage
ε	Eddy diffusivity
ε	Air–fuel ratio (by mass)
$\varepsilon_{A,B}$	Seebeck coefficient for material pair A, B
Δ	Increment in – usually used for indefinite integral, e.g. work (W), heat (Q)
ΔH_a	Atomisation energy
ΔH_f	Enthalpy of formation
$\Delta H()$	Dissociation energy
ε	Degree of reaction
ε	Air–fuel ratio of mixture
E	Heat exchanger effectiveness
κ	Ratio of specific heats (cp/cv)
λ	Electrical conductivity
λ	Equivalence ratio $= \varepsilon_{\text{stotic}}/\varepsilon$
μ	Dynamic viscosity
μ	Joule–Thomson coefficient
μ	Chemical potential
$\overline{\mu}$	Electrochemical potential
ν	Kinematic viscosity
$\pi_{A,B}$	Peltier coefficient for material pair A, B
θ	Entropy generation per unit volume
σ	Thomson coefficient
σr	Isentropic temperature ratio
σR	Pressure ratio for reheat
ν	Stoichiometric coefficient
γ	[C]/[C]e
γ	Ratio of maximum to minimum temperature in cycle
η	Efficiency
η_i	Isentropic efficiency of intake

η_j	Isentropic efficiency of nozzle
η_p	Propulsive efficiency (sometimes called Froude efficiency)
ϕ	Equivalence ratio
ρ	Density
ξ	Specific exergy
ψ	Inner electric potential of a phase
τ	Temperature ratio
Ξ	Exergy

Suffices

0	Dead state conditions
0	Stagnation conditions
a	Air (for gas turbine)
Actual	Value from actual cycle, as opposed to ideal cycle
av	Available (as in energy)
b	Backward (reaction)
b	Burned (products of combustion)
b	Bypass (gas turbines)
bdc	Bottom dead centre
B	Boiler
c	At critical point, e.g. pressure, temperature, specific volume
cc	Combustion chamber
cl	Clearance (volume, of cylinder)
C	Cold (as in temperature of reservoir)
C	Compressor
d	Diagram factor in engine *p*–*V* calculation
e	Flow out of system (exit)
evo	Exhaust valve opening
$[\ ]_e$	Equilibrium molar density
f	Forward (reaction)
f	Value for saturated liquid, e.g. h_f = enthalpy of saturated liquid
fg	Difference between properties on saturated vapour and saturated liquid lines, i.e. $h_{fg} = h_g - h_f$
g	Value for saturated gas, e.g. h_g = enthalpy of saturated gas
g	Gaseous state (as in reactants or products)
h	Constant enthalpy
H	Hot (as in temperature of reservoir)
i	Inversion
i	Flow into system
i	Indicated
i	*i*th constituent
ig	Ignition
in	Into system
isen	Isentropic (as in a process)
ivc	Inlet valve closure
j	Jet property
latent	Energy required for evaporation (equals h_{fg} or u_{fg})