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Principles of Engineering Thermodynamics

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Second Edition

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'Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, it doesn't bother you any more.'

Attributed to Arnold Sommerfeld with acknowledgement to S. W. Angrist and L. G. Hepler. *Order and Chaos!* Basic Books, London and New York (1967).

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Preface to First Edition

The emergence of mankind from the primitive world has been marked, and indeed made possible, by an increasing familiarity with the many forms of energy that exist in nature. In England for example the useful conversion of chemical energy to mechanical energy through the medium of heat was one of the cornerstones of the Industrial Revolution some two centuries ago, but the steam engines of those early days were mainly practical achievements developed by intuition and rule-of-thumb, with little insight into the principles involved. Steadily however theory caught up with, and eventually directed, the design of heat-work devices of all kinds, and the subject of thermodynamics is now firmly established as one of the most general theories of physical science, with ramifications far beyond the fields of energy transfer and conversion.

The teaching of thermodynamics has undergone corresponding developments, particularly in recent years. Formerly, each application of the subject was presented separately with its related packet of theory, and very often in chronological order of development, but nowadays emphasis is placed on the fundamental concepts in order to show the broad relationships, rather than the differences, between the many applications. Again, it was customary—and in some teaching schemes the tendency persists—for the physical nature of thermodynamic fluids to be presented first, and subsequently the thermodynamic laws themselves. In the present work, however, thermodynamic considerations of energy forms, energy transfer and energy conversion are dealt with in the first half of the book, and only then are the physical properties of fluids introduced. The thermodynamic behaviour of these fluids can be appreciated with greater ease following the initial grounding in the nature of energy. Applications to heat and work processes and cycles in practice are then arranged in an order that is systematic, with no restrictions of chronology. In this way, an integrated view of the subject is presented, with fundamentals and applications in proper perspective.

Many textbooks exist in the field of thermodynamics, with differing degrees of breadth and depth of treatment. The prime objective of the present work is to identify and explain the main principles on which the subject is based, and to present them in as concise a form as possible without losing essential detail.

This approach can be helpful both to the learner, who may otherwise become lost in a wealth of information, and to those seeking rapid revision.

The material is presented in the conventional chapter-and-section format, with related worked examples, test questions and problems. At appropriate points in the text the reader is referred back to derivations in earlier sections. In some cases applications or further developments of given concepts are foreshadowed by reference to later sections, but these need not be followed up in a first reading since their greatest value lies in tying together the various aspects of the subject during revision.

Being concerned directly with principles, the book lends itself to most syllabuses on the subject, up to and including first-degree level. However, such topics as entropy, availability and free energy do not figure largely in the more elementary types of examination syllabus, and in these cases may be studied in less detail. Other topics, such as gas analysis for air-fuel ratio determination, are not included since they are more properly handled elsewhere, for example, in books on fuels and combustion. Since a broad experience in problem solving is recommended, attention is drawn to several textbooks where further examples may be found.

Acknowledgement is made gratefully to colleagues and students of the University of Newcastle, N.S.W., and the Cranfield Institute of Technology, Milton Keynes, for much valued assistance in the form of discussion and feedback, and particularly to Professor A. H. Lefebvre, Head of the School of Mechanical Engineering, Cranfield, for the facilities made available to enable this work to be prepared.

Cranfield, 1974

E. M. Goodger

Preface to Second Edition

The aims of this second edition are to provide a systematic, consistent and concise treatment of engineering thermodynamics in a manner suited to both initial learning and revision, as before, and also to incorporate the experience gained from the first edition. It seeks therefore to identify and clarify the major aspects of the subject, and to arrange them into a pattern that develops the argument in a logical manner without the complication of the many fascinating side issues. These are available in the larger textbooks, and can be mastered more easily by subsequent study.

The energy foundation on which this book is built consists of concentrating first on energy forms, transfers and conversions before proceeding to the behaviour of idealised fluids and their applications to practical processes and cyclic devices and plant. Particular care has been taken over the mathematical sign convention used, which is a common source of confusion. Some approaches define the signs to suit the argument in hand but, in this book, the standard thermodynamic convention has been explained carefully and then used consistently, hence the reader can refer to any section in the certain knowledge of the meaning of each sign.

The material contained in the first edition has been in continuing use as a basis for lectures at Cranfield and elsewhere, and has generated valuable feedback both on matters of detail from successive groups of students, and on the wider issues from the reviewers, all of which is greatly appreciated. One review criticism raised, quite rightly, was that in some areas the book was brief rather than concise. This oversight arose because the areas concerned are customarily dealt with thoroughly in parallel lectures, and so are covered elsewhere for the student following a formal course. For the general reader, however, such superficial treatment is quite unhelpful, consequently this present edition is more balanced, with the needs of both undergraduate student and general reader firmly in mind. In particular, greater coverage is given to such topics as units, exergy, hygrometry, rotary compressors and expanders, heat exchange, cycle analysis and combined-cycle plant.

The energy approach adopted here has attracted some interest, including a suggestion that this aspect be developed further at the expense of the comprehensive analyses of the various thermodynamic processes. This suggestion is not

accepted, however, since such a philosophical exercise seems more suited to subsequent study.

The opportunity has been taken to make several improvements in clarity and accuracy, including the correction of one or two mis-statements that had escaped detection. It is hoped that this second offering will have cause to earn itself a place amongst the considerable literature on the subject, that its systematic energy-based presentation will help many who find difficulty with this very fundamental subject, and that suggestions for further improvement will continue to be forthcoming.

In preparing this revision, acknowledgement is made gratefully to Professor R. S. Fletcher, academic colleagues and students of the Cranfield School of Mechanical Engineering, and to the SME Drawing Office for its continuing excellence in preparing the illustrations.

Cranfield, 1984

E. M. Goodger

Units

In any system of units, a number of quantities are defined as fundamental to the system, and all the remaining quantities derived from them. If the system is coherent, the products and quotients of any two or more unit quantities themselves become the units of the derived quantities, in the absence of any conversion factors or proportionality constants. The rationalised system of metric units known as SI (Système International d'Unités) is coherent in this way, and applies to all branches of science and engineering.

The quantities and units of interest in this study consist of the following.

	<i>Quantity</i>	<i>Unit</i>	<i>Symbol</i>
(Fundamental)	length	metre	m
	mass	kilogram	kg
	time	second	s
	electric current	ampere	A
	thermodynamic temperature	kelvin	K
	amount of substance	mole	mol
(Derived)	force	newton	N (= kg m/s ²)
	pressure	pascal	Pa (= N/m ²)
	energy	joule	J (= N m)
	power	watt	W (= J/s)

The kelvin is also applied to temperature intervals. The mole relates to what was formerly called the 'gram-mole' and not to the 'kilogram-mole (kmol)'.

No change is made to any symbol to indicate the plural, and quantities are generally expressed in units that result in numerical values between 0.1 and 1000; preferred single multiples and submultiples differ in stages of 10 raised to a power that is a multiple of ± 3 , ranging normally from 10^{18} , exa, to 10^{-18} , atto.

SI has been adopted by many industries, some of which also use earlier metric units (litre, bar, centipoise, centistokes) together with non-metric units (atmosphere) which are considered acceptable. Since the adoption of SI is not yet worldwide, the following conversion factors and other metric relationships are given.

Length	1 in = 25.4 mm 1 ft = 0.304 8 m 1 mile = 1.609 km
Volume	1 ft ³ = 0.028 32 m ³ 1 UKgal = 1.201 USgal = 4.546 l 1 US gal = 0.832 7 UKgal = 3.785 l
Mass	1 lb = 0.453 6 kg 1 (long) ton = 2240 lb = 1016 kg 1 short ton = 2000 lb = 907.6 kg 1 tonne = 0.984 2 (long) ton = 1000 kg = 1 Mg
Density	1 lb/ft ³ = 16.02 kg/m ³
Force	1 lbf = 4.448 N
Pressure	1 lbf/in ² = 6.895 Pa 1 mm Hg = 133.3 Pa 1 atm = 1.013 25 bar = 101 325 kPa 1 bar = 100 kPa = 10⁵ Pa
Energy	1 Btu = 1.055 kJ 1 Chu = 1.899 kJ 1 kcal (international table) = 4.186 8 kJ 1 kcal (thermochemical) = 4.184 kJ 1 kWh = 3.6 MJ 1 hph = 2.685 MJ 1 therm = 10⁵ Btu = 105.5 MJ
Specific energy	1 Btu/lb = 2.326 kJ/kg 1 Chu/lb = 4.186 8 kJ/kg
Specific energy capacity	1 Btu/lb °R = 1 Chu/lb K = 4.186 8 kJ/kg K
Energy density	1 Btu/ft ³ = 0.037 26 kJ/l (or MJ/m ³) 1 Chu/ft ³ = 0.067 07 kJ/l (or MJ/m ³) 1 Btu/UKgal = 0.232 1 kJ/l (or MJ/m ³)
Power	1 hp = 745.7 W
Temperature	K = °C + 273.15 °F = (9/5)°C + 32 °R = °F + 459.67

(Figures in **bold type** are exact)

The current SI has developed from earlier systems based on gravitational units and on technical units. The confusion that sometimes arises over the use of units in engineering is generally due not so much to these unit systems themselves, but because the same metric-type units can appear in more than one system, and because the earlier systems still have their devotees. An overall understanding of relevant units is important in any subject, but the following attempt at disentanglement is limited to all that is necessary in the present context.

From Newton's Law of Gravitation, two bodies of masses m and m' , with their centres displaced by a distance r , exert between their centres attractive forces on each other of magnitude F given by

$$F = k_G \frac{mm'}{r^2}$$

where k_G is a *universal* gravity constant equal to $6.673\,2 \times 10^{-11} \text{ N m}^2/\text{kg}^2$.

In most everyday applications of gravity, the major body is the Earth which has a mass m' of approximately $5.98 \times 10^{24} \text{ kg}$ and radius r of approximately $6.37 \times 10^6 \text{ m}$. The gravitational weight force F_w exerted per unit mass of a relatively small body of mass m located on the surface of the Earth is given by

$$\begin{aligned} \frac{F_w}{m} &= k_G \frac{m'}{r^2} \\ &= 9.806\,65 \text{ N/kg} \end{aligned} \quad (1)$$

where this value applies to the Earth only and is *not* a universal constant.

This expression was then related to Newton's Second Law of Motion, given by

$$\begin{aligned} F &\propto ma \\ &= (1/g_c) ma \end{aligned} \quad (2)$$

where g_c can be described as a *universal* motion constant equal to 1 kg m/N s^2 , and a is the acceleration resulting from the action of the force on the mass. Comparison of (1) and (2) then indicates why, under the action of gravity at the surface of the Earth, a body falling freely in a vacuum is found to experience an acceleration given by

$$a = 9.806\,65 \text{ m/s}^2$$

The importance of terrestrial gravity to Earth-bound observers is such that a special symbol, g , has been adopted for this constant acceleration, where g applies to the Earth only and is *not* a universal constant. (On the surface of the Moon, for example, the corresponding value of gravitational acceleration is only 0.16 of the terrestrial value. It follows, nevertheless, that a force of 1 N applied in any direction to a body of mass 1 kg will produce an acceleration of $9.806\,65 \text{ m/s}^2$ in the direction of the applied force, and that this value is a universal constant for such conditions.)

The gravitational weight force per unit mass in equation (1) can now be written as

$$\begin{aligned} \frac{F_w}{m} &= \frac{g}{g_c} \\ &= \frac{9.806\,65}{1} \frac{\text{m/s}^2}{\text{kg m/N s}^2} \end{aligned} \quad (2)$$

It was then argued that, since g_c is unity in a coherent system of units such as SI, this term can be omitted in writing the above equation for Newton's Second Law of Motion on the understanding that it is incorporated by implication, thus

$F = mg$, with the $\frac{1}{g_c}$ omitted but implied

However, the essence of a coherent system is that the products and quotients of any two or more unit quantities are themselves the units of the derived quantities, in the absence of any constants of proportionality. Consequently, in SI, the expressions

$$F(\text{N}) = m (\text{kg}) a (\text{m/s}^2) \quad \text{generally} \quad (3)$$

and

$$F_w(\text{N}) = m (\text{kg}) g (\text{m/s}^2) \quad \text{specifically} \quad (4)$$

may be written directly with no need for constants or explanations of their invisible presence.

Expressions for potential and kinetic energies now follow by simple application of equations (3) and (4). If the surface of the Earth is adopted as the zero datum for potential energy, a body of mass m at height z above the Earth's surface (where z is small in relation to r so that F_w/m remains nominally constant) possesses a level of potential energy that is equivalent to the work done against its constant gravitational weight force in raising the body through the distance z . Thus

$$\begin{aligned} \text{Potential energy} &= E_P \\ &= \text{weight force} \times \text{vertical distance moved} \\ &= (mg)z \\ &= 9.80665 \, mz, \quad \text{J} \end{aligned} \quad (5)$$

The level of kinetic energy of a rigid body moving at velocity C relative to a given frame of reference can also be derived from similar reasoning, based on the work done in moving the body from rest, as follows

Elemental work done = force $\times$ elemental distance moved

$$\begin{aligned} dW &= F \, dx \\ &= (ma) \, dx \\ &= m \frac{dC}{dt} \, dx \\ &= m \frac{dx}{dt} \, dC \\ &= mC \, dC \end{aligned}$$

Thus

$$\begin{aligned} \text{Finite work done} &= W = m \int C \, dC \\ &= \text{Kinetic energy} = E_K = m \frac{C^2}{2} \end{aligned} \quad (6)$$

Physical Constants

k_G	universal gravity constant $= 6.673\ 2 \times 10^{-11}\ \text{Nm}^2/\text{kg}$
g_c	universal motion constant $= 1\ \text{kg m/N s}^2$
g	standard acceleration due to Earth's gravity $= 9.806\ 65\ \text{m/s}^2$
k_B	Boltzmann's constant $= 1.380\ 4 \times 10^{-23}\ \text{J/molecule K}$
N_0	Avogadro's number $= 6.024\ 7 \times 10^{26}\ \text{molecule/kmol}$
c_p	for air at 1 atm and $15^\circ\text{C} = 1.005\ \text{kJ/kg K}$
c_v	for air at 1 atm and $15^\circ\text{C} = 0.718\ \text{kJ/kg K}$
R	for air $= 0.286\ 7\ \text{kJ/kg K}$
R_0	universal gas constant $= 8.314\ 3\ \text{kJ/kmol K}$
V_M	molar volume of ideal gas $= 22.413\ 6\ \text{m}^3/\text{kmol}$ at 1 atm and 0°C $= 22.413\ 6\ \text{l/mol}$ atm and 0°C
σ	Stefan-Boltzmann constant $= 56.7 \times 10^{-12}\ \text{kW/m}^2\ \text{K}^4$

Standard atmospheric pressure = 1 atm = 101 325 Pa

Mean value of molar mass of air = 28.9 g/mol

Ice point of water = $0^\circ\text{C} = 273.15\ \text{K}$

Triple point of water = $0.01^\circ\text{C} = 273.16\ \text{K}$

Notation

When two symbols are given for one quantity, upper case represents extensive and lower case specific.

When one symbol is used for more than one quantity, the relevant sections are shown in parentheses.

A, a	Non-flow availability function
a	Sonic velocity (6.3.1)
B, b	Steady-flow availability function
C	Absolute velocity (2.1, 6.3)
C	Heat capacity, molar basis (5.3)
c	Specific heat capacity, mass basis
c	Clearance ratio (6.2.1)
E, e	Energy of a system
E_K, e_K	Kinetic energy
E_P, e_P	Potential energy
F, f	Helmholtz free energy function
G, g	Gibbs free energy function
g	Standard acceleration due to Earth's gravity
g_c	Universal motion constant
H, h	Enthalpy
I, i	Irreversibility
M	Molar mass
m	Mass
N	Number of cycles per minute
n	Number of moles (5.1)
n	Polytropic index (5.5)
p	Pressure
p	Probability (4.1)
Q, q	Heat transfer
R	Gas constant
R_0	Universal gas constant
r	Ratio
S, s	Entropy

T	Absolute, or thermodynamic, temperature, kelvin
t	Empirical temperature, °C
U, u	Internal energy
U	Tangential velocity of rotor (6.3)
V, v	Volume
V	Relative velocity (6.3)
W, w	Work transfer
w	Specific humidity (5.11)
X, x	Exergy
x	Dryness fraction of steam
Y, y	Anergy
z	Height above Earth's surface
α	Angular rotation (2.3.1)
α	Cut-off ratio in Diesel cycle (7.2)
β	Coefficient of performance
γ	Specific heat ratio, c_p/c_v
ϵ	Electrical potential (2.3.1)
ϵ	Effectiveness (4.3)
η	Efficiency
θ	Thermodynamic temperature (3.8)
θ	Exergetic potential (4.3)
ρ	Density
σ	Surface tension
τ	Torque
ϕ	$\int (c_p/T) dT$ (5.3)
ϕ	Relative vapour pressure (5.11)
ω	Angular velocity

Superscripts

0	Standard state of 25°C and 1 atmosphere
$'$	Internally-based (2.3.1)
$'$	Partial (5.8, 5.11)

Subscripts

A	Air
a	axial (6.3.2.1)
a	Atomisation (6.4)
B	Burner
b	Brake
c	Clearance
comp	Compressor
CR	Critical
d	Diagram

e	Energy
e	Expansion ratio (6.2.2)
envt	Environment
ex	Exhaust
F	Flow (2.3.1)
F	Fuel (6.4, 7.2.1)
f	Saturated liquid (5.10)
f	Free gas (6.2.1)
f	Formation (6.4)
fg	Difference between saturated vapour and saturated liquid
g	Saturated vapour
H	High-pressure stage
HP	Heat pump
I	Irreversible
i	Any arbitrary component of a mixture (5.8)
i	Inlet (6.3.2.1)
i	Indicated (7.2.1)
K	Kinetic
L	Low-pressure stage
m	Molar
O	Overall
o	Outlet (6.3.2.1)
o	Environmental (4.3)
P	Potential
<i>p</i>	Isobaric (3.3)
<i>p</i>	Pressure (7.3)
Pr	Product
R	Reversible
Rc	Reactant
REF	Refrigerator
r	Relative or reduced (5.3)
r	Reaction (6.4)
ref	Reference
s	Isentropic (4.1)
s	Saturated (5.10)
s	Swept (6.2.1)
T	Isothermal
t	Total head
turb	Turbine
ν	Isochoric (3.3, 5.5.5, 5.6.5)
v	Vapour (5.11)
ν	Volume (7.2)
w	Work
w	Whirl (6.3)
x	Exergy