Introduction to Internal Combustion Engines

Introduction to Internal Combustion Engines

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Third Edition

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Preface to the Third Edition

This book is intended to provide engineers and students with the background that is pre-supposed in many articles, papers and advanced texts. Since the book is primarily aimed at students, it has sometimes been necessary to give only outline or simplified explanations. However, numerous references have been made to sources of further information.

Internal combustion engines form part of most thermodynamics courses at Colleges and Universities. This book should be useful to students who are following specialist options in internal combustion engines, and also to students at earlier stages in their courses – especially with regard to laboratory work.

Practising engineers should also find the book useful when they need an overview of the subject, or when they are working on particular aspects of internal combustion engines that are new to them.

The subject of internal combustion engines draws on many areas of engineering: thermodynamics and combustion, fluid mechanics and heat transfer, mechanics, stress analysis, materials science, electronics and computing. However, internal combustion engines are not just subject to thermodynamic or engineering considerations – the commercial (marketing, sales etc.) and economic aspects are also important, and these are discussed as they arise.

In order to make this book self-contained, Appendix A now contains thermodynamic tables for combustion calculations; this should also ensure consistency in the answers if these tables are used in any calculations. The tables contain equilibrium constants and molar thermodynamic property data (internal energy, enthalpy, Gibbs energy and entropy) for the species to be found in the reactants and products. The datum for enthalpy adopted here is **zero enthalpy for elements when they are in their standard state at a temperature of 25°C**. The enthalpy of any molecule at 25°C will thus correspond to its enthalpy of formation, ΔH_f^0 . This choice of datum (although not used to my knowledge in any other tables) will be seen to facilitate energy balances in combustion. Unlike tables that use an identical datum for reactant and product species, there is no need to include enthalpies or internal energies of reaction. Chapter 3 now contains much new material to explain and illustrate the use of these tables. The relevant examples have been solved using the old and new approaches for two reasons. Firstly, to demonstrate that combustion problems can be analysed more simply using data presented in the format of Appendix A. Secondly, because some students may have to use the format in existing tables for their examinations.

Since the first publication of *Introduction to Internal Combustion Engines* the preferred practice for denoting molar quantities is to use a lower case letter (to emphasise that it is a specific quantity) with a tilde above, for example $\tilde{n}$. However, for consistency with the *Solutions Manual* (see below) (and in common with many other publications) molar quantities will be denoted here by upper case letters. This requires the reader to decide whether the symbol refers to a molar specific quantity or a property value of a complete system.

Preparing the third edition has also provided the opportunity to include further worked examples and many problems (with numerical answers). There is now a *Solutions Manual* available, which contains the questions, answers and the thermodynamic data that can be found here in Appendix A. The solutions manual is thus self-contained, and provides an opportunity for some additional discussion to be included.

The first six chapters still provide an introduction to internal combustion engines, and these can be read in sequence.

Chapter 1 provides an introduction, with definitions of engine types and operating principles. The essential thermodynamics is provided in chapter 2, while chapter 3 provides the background in combustion and fuel chemistry. The differing needs of spark ignition engines and compression ignition engines are discussed in chapters 4 and 5 respectively. Chapter 6 describes how the induction and exhaust processes are controlled.

Chapter 11 provides a discussion of some topics in the mechanical design of engines, and explains some of the criteria that influence material selection. Chapter 13 provides an overview of the experimental equipment that is an essential part of engine development. This chapter has substantial additions to describe gas analysis equipment and its use, and an introduction to computer-based combustion analysis.

The remaining chapters pre-suppose a knowledge of the material in the earlier chapters. Chapter 7 contains a treatment of two-stroke engines, a topic that has gained widened interest since the first edition; both spark ignition and compression ignition engines are discussed.

Chapter 8 is mainly concerned with turbulence: how it is measured, how it is defined and how it affects combustion. Such knowledge is pre-supposed in technical papers and the contributions in specialist texts.

Chapter 9 discusses the application of turbochargers to spark ignition and compression ignition engines, and there is further material on turbocharging in chapter 10 (Engine Modelling) as a turbocharged engine is used as an example.

The treatment of engine cooling in chapter 12 has been provided since it is a subject that is often overlooked, yet it is an area that offers scope for reductions in both fuel consumption and emissions.

The material in the book has been used by the author for teaching final year students, contributing to MSc Courses, and short courses for industry. These experiences have been invaluable in preparing the third edition, as have the written comments from readers. The material within the book has come from numerous sources. The published sources have been acknowledged, but of greater importance have been the conversations and discussion with colleagues and researchers in the area of internal combustion engines, especially when they have provided me with copies of relevant publications.

I would again welcome any criticisms or comments on the book, either concerning the detail or the overall concept.

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RICHARD STONE

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Notation

abdc	after bottom dead centre
atdc	after top dead centre
A	piston area (m^2)
A_c	curtain area for poppet valve (m^2)
A_e	effective flow area (m^2)
A_f	flame front area (m^2)
A_o	orifice area (m^2)
A/F	air/fuel ratio
bbdc	before bottom dead centre
bdc	bottom dead centre
bmep	brake mean effective pressure (N/m^2)
bsac	break specific air consumption
bsfc	brake specific fuel consumption
btdc	before top dead centre
B	bore diameter (m)
BHP	brake horse power
c	sonic velocity (m/s)
c_p	specific heat capacity at constant pressure (kJ/kg K)
c_v	specific heat capacity at constant volume (kJ/kg K)
C_D	discharge coefficient
C_o	orifice discharge coefficient
C_p	molar heat capacity at constant pressure (kJ/kmol K)
C_v	molar heat capacity at constant volume (kJ/kmol K)
CI	compression ignition
CV	calorific value (kJ/kg)
dc	direct current
dohc	double overhead camshaft
D_v	valve diameter (m)
DI	direct injection (compression ignition engine)
DISI	direct injection spark ignition
EGR	exhaust gas recirculation
f	fraction of exhaust gas residuals
ff	turbulent flame factor
fmep	frictional mean effective pressure
fwd	front wheel drive
g	gravitational acceleration (m/s^2)
G	Gibbs energy (kJ/kg)
GDI	gasoline direct injection
h	specific enthalpy (kJ/kg); manometer height (m)
h_d	mean height of indicator diagram (m)

H	enthalpy (kJ)
HCV	higher calorific value (J/kg)
imep	indicated mean effective pressure (N/m ²)
isac	indicated specific air consumption (kg/MJ)
isfc	indicated specific fuel consumption (kg/MJ)
I	current (A)
IDI	indirect injection (compression ignition engine)
jv	just visible (exhaust smoke)
k	constant
K	equilibrium constant
KLSA	knock limited spark advance
l	length, connecting-rod length (m)
l_b	effective dynamometer lever arm length (m)
l_d	indicator diagram length (m)
L	stroke length (m); inductance (H)
L_D	duct length (m)
L_v	valve lift (m)
LBT	lean best torque
LCV	lower calorific value (J/kg)
LDA	laser Doppler anemometer
LDV	laser Doppler velocimeter
m	mass (kg)
$\dot{m}_a$	air mass flow rate (kg/s)
$\dot{m}_f$	fuel mass flow rate (kg/s)
m_r	reciprocating mass (kg)
M	mutual inductance (H); molar mass (kg); moment of momentum flux (N/m)
MBT	minimum (ignition) advance for best torque (degrees)
n	number of moles, cylinders
N^*	rev/s for two-stroke, rev/2s for four-stroke engines
N'	total number of firing strokes/s ($\equiv n.N^*$)
NMO	non-methane organic gases
Nu	Nusselt number (dimensionless heat transfer coefficient)
ohc	overhead camshaft
ohv	overhead valve
p	pressure (N/m ²)
p'	partial pressure (N/m ²)
$\bar{p}$	mean effective pressure (N/m ²)
Pr	Prandtl number (ratio of momentum and thermal diffusivities)
Q	heat flow (kJ)
r	crankshaft throw ($\equiv 1/2$ engine stroke) (m)
r_p	pressure ratio
r_v	volumetric compression ratio
R	specific gas constant (kJ/kg K)
R_o	molar (or universal) gas constant (kJ/kmol K)
Re	Reynolds number
s	specific entropy (kJ/kg K)
sac	specific air consumption (kg/MJ); this usually means brake specific air consumption
sfc	specific fuel consumption (kg/MJ); this usually means brake specific fuel consumption
S_L	laminar flame speed

S_V	laminar burning velocity
SI	spark ignition
t	time (s)
tdc	top dead centre
T	absolute temperature (K); torque (N m)
T_0	absolute temperature of the environment (K)
u_p	laminar flame front velocity (m/s)
u_t	turbulent flame front velocity (m/s)
U	internal energy (J)
v	velocity (m/s)
$\bar{v}_p$	mean piston velocity (m/s)
V	volume (m ³)
$\dot{V}_a$	volumetric flow rate of air (m ³ /s)
V_s	engine swept volume (m ³)
VCO	valve covered orifice
wmmp	weakest mixture for maximum power
W	work (kJ)
$\dot{W}$	power (kW)
W_b	brake work (kJ)
W_c	compressor work (kJ)
W_f	friction work (kJ)
W_i	indicated work (kJ)
W_{REV}	work output from a thermodynamically reversible process (kJ)
W_t	turbine work (kJ)
WOT	wide open throttle
x	a length (m); mass fraction
Z	Mach index
α	cut-off (or load) ratio
γ	ratio of gas heat capacities, c_p/c_v or C_p/C_v
ΔH_0	enthalpy of reaction (combustion) $\equiv -CV$
Δp	pressure difference (N/m ²)
$\Delta\theta_b$	combustion duration (crank angle, degrees)
ε	heat exchanger effectiveness = (actual heat transfer)/(max. possible heat transfer)
η	efficiency
η_b	brake thermal efficiency $\equiv \eta_o$
η_c	isentropic compressor efficiency
η_{Diesel}	ideal air standard Diesel cycle efficiency
η_{FA}	fuel–air cycle efficiency
η_i	indicated (arbitrary overall) efficiency
η_m	mechanical efficiency
η_o	arbitrary overall efficiency
η_{Otto}	ideal air standard Otto cycle efficiency
η_R	rational efficiency, W/W_{REV}
η_t	isentropic turbine efficiency
η_v	volumetric efficiency
θ	crank angle (degrees)
θ_0	crank angle at the start of combustion (degrees)
μ	dynamic viscosity (N s/m ²)
ρ	density (kg/m ³)
ρ_u	density of the unburnt gas (kg/m ³)

ϕ	equivalence ratio = (stoichiometric air/fuel ratio)/(actual air/fuel ratio) (<i>note that</i> sometimes the reciprocal definition is used in other publications)
ω	specific humidity (kg water/kg dry air); angular velocity (rad/s)

Suffixes

a	air
b	brake
c	compressor
f	friction
i	indicated, chemical species
m	mechanical
t	turbine
v	volumetric