Introduction to Internal Combustion Engines

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Second Edition

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Preface to the Second Edition

This book aims to provide for students and engineers 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 Polytechnics 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.

The second edition contains significant new material, both within the original chapters and in the new chapters. Preparing the second edition has also provided the opportunity to include further worked examples and many problems (with numerical answers).

The first 6 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 turbo-charging 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 a final year course at Brunel, and contributing to the MSc in Automotive Product Engineering at Cranfield. These experiences have been useful in preparing the second 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 equal importance have been the conversations and discussion with colleagues and researchers in the area of internal combustion engines.

It is invidious to acknowledge individuals, but I must thank my colleague Dr Nicos Ladommatos for making a stimulating research environment in engines at Brunel. I must also thank Mrs June Phillips for her tireless and efficient typing of the manuscript.

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

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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)
E	absolute internal energy (kJ)
EGR	exhaust gas recirculation
f	fraction of exhaust gas residuals

ff	turbulent flame factor
f_{mep}	frictional mean effective pressure
fwd	front wheel drive
g	gravitational acceleration (m/s^2)
G	Gibbs function (kJ)
h	specific enthalpy (kJ/kg); manometer height (m)
h_d	mean height of indicator diagram (m)
H	enthalpy (kJ)
i_{mep}	indicated mean effective pressure (N/m^2)
I	current (A)
IDI	indirect injection (compression ignition engine)
j_v	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
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 2-stroke, rev./2s for 4-stroke engines
N'	total number of firing strokes/s ($\equiv n.N^*$)
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 ($\equiv \frac{1}{2}$ engine stroke) (m)
r_p	pressure ratio

r_v	volumetric compression ratio
R	specific gas constant (kJ/kg K)
R_0	molar (or universal) gas constant (kJ/kmol K)
Re	Reynolds number
s	specific entropy (kJ/kg K)
sac	specific air consumption (kg/MJ)
sfc	specific fuel consumption (kg/MJ)
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_1	laminar flame front velocity (m/s)
U_t	turbulent flame front velocity (m/s)
v	velocity (m/s)
$\bar{v}_p$	mean piston velocity (m/s)
$\dot{V}$	volume (m ³)
$\dot{V}_a$	volumetric flow rate of air (m ³ /s)
V_s	engine swept volume (m ³)
wmmp	weakest mixture for maximum power
$\dot{W}$	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
m	mechanical
t	turbine
v	volumetric