Introduction to Internal Combustion Engines

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Preface

This book aims to provide for students and engineers the background that is presupposed 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. These disparate areas are drawn together in the first eight chapters, so that these chapters are best read in sequence. 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.

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, and this leads to chapter 7, where turbochargers are discussed. The remaining chapters can be read in parallel with the earlier chapters. Some of the mechanical and materials aspects are discussed in chapter 8, while chapter 9 covers some experimental techniques. Finally, chapter 10 provides three case studies that should remain topical for some time.

This book is the product of information gained from numerous sources, and it would be invidious to acknowledge individuals. However, I should like to express my gratitude to Dr Neil Watson of Imperial College, London, and to Dr Neil Richardson of Jesus College, Oxford, for reading and commenting on the drafts. I must also express my thanks to the typists, in particular to Mrs Gill Oxley who typed most of the material.

In conclusion, I would welcome any criticism and suggestions concerning either the detail of the book or the overall concept.

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Notation

a	sonic velocity (m/s)
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)
btdc	before top dead centre
BHP	brake horse power
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/kg K)
C_v	molar heat capacity at constant volume (kJ/kg 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
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)
imep	indicated mean effective pressure (N/m^2)
I	current (A)
IDI	indirect injection (compression ignition engine)
jv	just visible (exhaust smoke)
k	constant
K	equilibrium constant
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)
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)
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)
$\bar{p}_b$	brake 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_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)
sfc	specific fuel consumption (MJ/kg)
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_l	laminar flame front velocity (m/s)
U_t	turbulent flame front velocity (m/s)
v	velocity (m/s)
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)
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
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)
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) (*note that* sometimes the reciprocal definition is used in other publications)
ω	specific humidity (kg water/kg dry air); angular velocity (rad/s)

Contents

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1 Introduction

1.1 Fundamental operating principles

The reciprocating internal combustion engine must be by far the most common form of engine or prime mover. As with most engines, the usual aim is to achieve a high work output with a high efficiency; the means to these ends are developed throughout this book. The term 'internal combustion engine' should also include open circuit gas turbine plant where fuel is burnt in a combustion chamber. However, it is normal practice to omit the prefix 'reciprocating'; none the less this is the key principle that applies to both engines of different types and those utilising different operating principles. The divisions between engine types and between operating principles can be explained more clearly if stratified charge and Wankel-type engines are ignored initially; hence these are not discussed until section 1.4.

The two main types of internal combustion engine are: spark ignition (SI) engines, where the fuel is ignited by a spark; and compression ignition (CI) engines, where the rise in temperature and pressure during compression is sufficient to cause spontaneous ignition of the fuel. The spark ignition engine is also referred to as the petrol, gasoline or gas engine from its typical fuels, and the Otto engine, after the inventor. The compression ignition engine is also referred to as the Diesel or oil engine; the fuel is also named after the inventor.

During each crankshaft revolution there are two strokes of the piston, and both types of engine can be designed to operate in either four strokes or two strokes of the piston. The four-stroke operating cycle can be explained by reference to figure 1.1.

(1) The induction stroke. The inlet valve is open, and the piston travels down the cylinder, drawing in a charge of air. In the case of a spark ignition engine the fuel is usually pre-mixed with the air.
(2) The compression stroke. Both valves are closed, and the piston travels up the cylinder. As the piston approaches top dead centre (tdc), ignition occurs. In the case of compression ignition engines, the fuel is injected towards the end of the compression stroke.

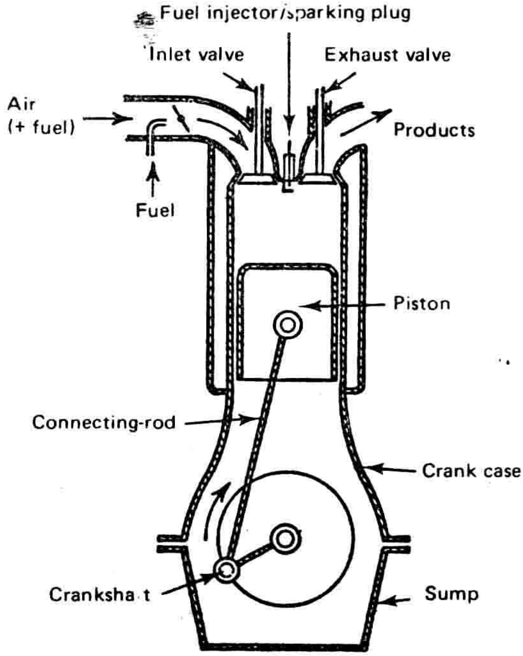

Figure 1.1 A four-stroke engine (reproduced with permission from Rogers and Mayhew (1980a))

(3) The expansion power or working stroke. Combustion propagates throughout the charge, raising the pressure and temperature, and forcing the piston down. At the end of the power stroke the exhaust valve opens, and the irreversible expansion of the exhaust gases is termed 'blow-down'.
(4) The exhaust stroke. The exhaust valve remains open, and as the piston travels up the cylinder the remaining gases are expelled. At the end of the exhaust stroke, when the exhaust valve closes some exhaust gas residuals will be left; these will dilute the next charge.

The four-stroke cycle is sometimes summarised as 'suck, squeeze, bang and blow'. Since the cycle is completed only once every two revolutions the valve gear (and fuel injection equipment) have to be driven by mechanisms operating at half engine speed. Some of the power from the expansion stroke is stored in a flywheel, to provide the energy for the other three strokes.

The two-stroke cycle eliminates the separate induction and exhaust strokes; and the operation can be explained with reference to figure 1.2.

(1) The compression stroke (figure 1.2a). The piston travels up the cylinder, so compressing the trapped charge. If the fuel is not pre-mixed, the fuel is injected towards the end of the compression stroke; ignition should again