Turbocharging
the Internal Combustion Engine

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Preface

The turbocharger was invented a surprisingly long time ago but only relatively recently has it been an accepted component on all but very small diesel engines. After several false starts they are now also being used on petrol engines. Unlike most other components of an engine, the turbocharger can radically transform the performance of the engine and is therefore very much a critical component. As a result more engineers need to understand how and why it does what it does.

The characteristics of turbomachines are fundamentally different from those of reciprocating machines, hence the combination of turbocharger and engine has many complex characteristics. Yet engineers with diesel or petrol engine experience have little knowledge of turbomachines, and vice versa, and are therefore not well equipped to optimise the combination. This book is an attempt to help these engineers by explaining the principles of turbocharging, with special emphasis on the interactions between engine and turbocharger. Many examples of the current practice of turbocharging are also given to explain how the principles can be used to advantage. Although examples relating to large industrial and marine engines are not omitted, preference has deliberately been given to examples of practice on automotive (truck-type) diesel engines for several reasons. Firstly turbocharging is longer established on marine and industrial engines and hence the principles are better known in that industry. Secondly engine designers, development engineers and users who are new to turbocharging are mainly involved with truck and passenger car diesel engines.

The application of turbocharging to passenger car petrol engines has many unique features and therefore a special chapter has been devoted to this subject.

The authors, as academics, are firmly convinced that an understanding of the basic theory underlying a subject will lead the engineer to make wiser decisions. It is common practice to present this theory to students through mathematics, as the language of the engineer. This book is aimed at both the student and the practising engineer and the authors have recognised that the latter finds a mathematical approach tedious. As far as possible therefore explanations of principles have been presented in words and not through mathematics, so that the book is more readable than it would otherwise be. However, the techniques of analysis, mathematics and computer-aided design are now so useful to the engine designer that they should not be ignored. The mathematical representation of turbocharged engines has therefore been treated in a chapter of its own at the end of the book (chapter 15).

The organisation of the book is based on the premise that most readers will know more about engines than turbomachines. Following a brief over-all introduction to turbocharging, chapters 2 to 5 are devoted to the construction of turbochargers and the principles of radial compressors and radial and axial turbines, with reference to the turbocharger application (axial compressors are not used on turbochargers, being more suited for larger and more expensive gas turbines). Some readers may wish to omit the detailed description of flow processes in the turbomachines. Chapters 6 to 9 are concerned with turbocharging systems and the best methods of utilising exhaust gas energy via the turbocharger. Chapter 10 describes the critical task of matching the turbomachine to the engine to achieve optimum performance of the combination for all the common applications. Chapters 11, 12, 13 and 14 are concerned with factors specific to or important in certain applications such as high-output turbocharging, transient performance, applications to petrol engines and the effect of turbocharging on exhaust emissions. The final chapter (15) has been mentioned above.

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N. WATSON
M. S. JANOTA

Marian Janota died shortly before the publication of this book. We had completed every stage in preparing the book but sadly he did not see the final bound volume.

N. WATSON
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Nomenclature

a	sonic velocity	m/s
a'	non-dimensional sonic velocity, a/a_{ref}	–
A	area	m^2
ABDC	above bottom dead centre	–
ADR	air delivery ratio	–
AFR	air/fuel ratio	–
AR	area ratio	–
AS	aspect ratio	–
b	width	m
B	cylinder bore	m
BBDC	below bottom dead centre	–
BDC	bottom dead centre	–
BMEP	brake mean effective pressure	bar
BS	brake specific value	–
BSAC	brake specific air consumption	g/kW h
BSFC	brake specific fuel consumption	g/kW h
c_p	specific heat at constant pressure	kJ/kg K
c_v	specific heat at constant volume	kJ/kg K
C	velocity	m/s
C'	non-dimensional velocity, C/a_{ref}	–
Cd	discharge coefficient	–
Ch	enthalpy loss coefficient	–
C_{LF}	lift coefficient, per unit length	–
CP, CPR	pressure recovery coefficient	–
CPL	pressure loss coefficient	–
CR	compression ratio	–
CTQ	torque coefficient	–
D	diameter	m
Df	diffusion factor	–
DI	direct injection diesel engine	–
DS	specific diameter	–
E	energy	kJ
EC	exhaust port or valve closes	°
EO	exhaust port or valve opens	°

ER	expansion ratio	–
EVC	exhaust valve closes	°
EVO	exhaust valve opens	°
f	frequency; friction factor; function; burnt fuel/ air ratio	Hz; –
F	equivalence ratio; force	–; kN
FB	fuel burnt	–
FBR	fuel burning rate	–
FL	frictional loss as torque	N m
FMEP	frictional loss as loss of mean effective pressure	bar
FP	fuel prepared	kg
FR	fuel reacted	kg
h	height; specific enthalpy	m; kJ/kg
HD	pressure head	m^2/s^2
hf	humidity factor	–
HSU	Hartridge smoke units	–
HP	high pressure	–
ht	heat transfer coefficient	kW/m^2 K
i	incidence angle; control volume number	°; –
I	section modulus (inertia)	kg m^2
IC	inlet port or valve closes	°
ID	ignition delay	°
IDI	indirect injection diesel engine	–
IMEP	indicated mean effective pressure	bar
IO	inlet port or valve opens	°
IVC	inlet valve closure	–
k	conductivity; constant	kW/m K; –
K	general constant	–
KE	kinetic energy	J
l	length, chord	m
L	losses	–
LF	lift force	kN
LP	low pressure	–
LT	load torque	N m
m	mass	kg
$\dot{m}$	mass flow rate	kg/s
M	Mach number	
MBT	maximum brake torque	–
MR	Mach number ratio	–
n	number	–
N	rotational speed	rev/min
NA	naturally aspirated	–
ND	specific diameter	–
NS	specific speed	–
Nu	Nusselt number	–
P	pressure	bar
PE	potential energy	J
PP	partial pressure	bar

ppm	parts per million (concentration)	–
Pr	Prandtl number	–
PR	pressure ratio	–
Q	heat transfer	kJ
$\dot{Q}$	heat transfer rate	kW
r	radius	m
R	gas constant	kJ/kg K
Re	Reynolds number	–
RN	degree of reaction	–
RPM	revolutions per minute	min^{-1}
s	specific entropy	kJ/kg K
sp	circumferential spacing (pitch)	m
t	time	s
t'	non-dimensional time, ta_{ref}/l_{ref}	–
T	temperature	K
TC	turbocharged	–
TDC	top dead centre	–
th	thickness	m
TQ	torque	N m
u	specific internal energy	kJ/kg
U	rotor tip speed	m/s
v	specific volume	m^3/kg
V	volume	m^3
$\dot{V}$	volumetric flow rate	m^3/s
vo	valve opening period	°
W	work done; velocity relative to blade	kJ; m/s
$\dot{W}$	power	kW
x	distance; relative change in rack movement	m
x'	non-dimensional distance, x/l_{ref}	–
y	relative change in speed	m/s
z	number of nozzles or vanes	–
Z	number of blades	–
α	angle	°
β	backsweep angle; phase proportionality factor; Riemann parameter	°; –
γ	c_p/c_v	–
Δ	increment	–
ϵ	effective impeller exit area ratio; arc of admission; effectiveness; emissivity	–; °; –; –
η	efficiency	–
θ	angle	°
λ	Riemann parameter	–
Λ	r_{hub}/r_{tip}	–
μ	dynamic viscosity; energy transfer coefficient	kg/m s; kg m/s
ν	Poisson's ratio; kinematic viscocity	–; m^2/s^2
ρ	density	kg/m^3
σ	compressor slip factor; Stephan-Boltzmann constant; stress	–; $kW/m^2\ K^4$; kN/m^2

ϕ	angle; relative humidity	°; –
ψ	azimuth angle; blade loading coefficient	°; –
ω	angular velocity	rad/s

Subscripts

a	axial; air; ambient	n	nozzle
alt	altitude	NOM	nominal
an	anemometer	p	exhaust pipe; polytropic
APP	apparent	p	pressure
b	blade; backsweep	P	profile
bu	bursting	pis	piston
c	compressor; centrifugal	q	casing (exit)
carb	carburettor	r	radial; root
cl, C	clearance	R	rotor
com	combustion	ref	reference
cool	coolant	rel	relative
cyl	cylinder	s	isentropic
dif	diffuser	S	secondary
e	engine; trailing edge	ss	isentropic throughout
es	end of sector	sf	surface
ex	exhaust	sh	shroud
f	fuel	st	stalled
fb	fuel burnt	sto	stoichiometric
for	formation	svp	saturated vapour pressure
fr	friction	sw	swept
g	gas	t	turbine; tip
gb	gas bending	tc	turbocharger
ge	gas exchange	th	throat
h	hoop; hub	tot	total
ht	heat transfer	TS	total to static
i	instantaneous	TT	total to total
ic	inlet casing	u	unburnt fuel
imp	impeller	ult	ultimate
ind	indicated	v	volume
j	control volume port	vol	volumetric
k	casing (inlet)	w	water, windage
l	load	z	start of compression
m	manifold; mean	*	naturally aspirated
max	maximum	0	stagnation
min	minimum	θ	tangential
mot	motored	ω	whirl