

Klaus Mollenhauer
Helmut Tschöke
Eds.

Handbook of Diesel Engines

 Springer

 **BOSCH**

Klaus Mollenhauer · Helmut Tschoeke

Handbook of Diesel Engines

Klaus Mollenhauer · Helmut Tschoeke

Handbook of Diesel Engines

With 584 Figures and 86 Tables

 Springer

Editors

Prof. Dr.-Ing. Klaus Mollenhauer
Orber Str. 25
14193 Berlin
Germany
Klamoll@aol.com

Prof. Dr.-Ing. Helmut Tschoeke
Otto von Guericke University Magdeburg
Institute of Mobile Systems
Universitätsplatz 2
39106 Magdeburg
Germany
helmut.tschoeke@ovgu.de

Translator

Krister G. E. Johnson
Otto-von-Guericke-Strass 56 b
39104 Magdeburg
Germany

ISBN 978-3-540-89082-9 e-ISBN 978-3-540-89083-6

DOI 10.1007/978-3-540-89083-6

Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2010924045

© Springer-Verlag Berlin Heidelberg 2010

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover design: WMXDesign GmbH, Heidelberg

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This machine is destined to completely revolutionize engine engineering and replace everything that exists. (From Rudolf Diesel's letter of October 2, 1892 to the publisher Julius Springer.)

Although Diesel's stated goal has never been fully achievable of course, the diesel engine indeed revolutionized drive systems. This handbook documents the current state of diesel engine engineering and technology. The impetus to publish a Handbook of Diesel Engines grew out of ruminations on Rudolf Diesel's transformation of his idea for a rational heat engine into reality more than 100 years ago. Once the patent was filed in 1892 and work on his engine commenced the following year, Rudolf Diesel waited another 4 years until the Association of German Engineers provided him a platform to present his engine to the public at its convention in Kassel on June 16, 1897. The engine came to bear the name of its ingenious inventor soon thereafter.

The editors and publisher intend this English edition of the handbook to furnish readers outside German-speaking regions a scholarly and practical presentation of the current state of the diesel engine and its large range of applications. The handbook has not only been conceived for diesel experts but also "diesel laypersons" with prior knowledge of engineering or at least an interest in technology. Furthermore, it is intended to benefit students desiring a firsthand comprehensive and sound overview of diesel engine engineering and technology and its state of development.

These aims are reflected in the book's five-part structure. Part I provides a brief history of the diesel engine followed by sections on the fundamentals, including supercharging systems, diesel engine combustion, fuels and modern injection systems. Parts II–IV treat the loading and design of selected components, diesel engine operation, the pollution this causes and the increasingly important measures to reduce it. Part V presents the entire range of engines from small single

cylinder diesel engine up through large low speed two-stroke diesel engines. An appendix lists the most important standards and regulations for diesel engines.

Further development of diesel engines as economizing, clean, powerful and convenient drives for road and nonroad use has proceeded quite dynamically in the last twenty years in particular. In light of limited oil reserves and the discussion of predicted climate change, development work continues to concentrate on reducing fuel consumption and utilizing alternative fuels while keeping exhaust as clean as possible as well as further increasing diesel engine power density and enhancing operating performance. Development is oriented toward the basic legal conditions, customer demands and, not least, competition with gasoline engines, which are still considered the benchmark car engine in many sectors.

The topics to be treated were weighed with all this in mind: In addition to engine internal measures that reduce exhaust emissions with the aid of new combustion systems and new fuels, the section on *Exhaust Gas Aftertreatment* deserves particular mention. The oxidation catalytic converters introduced in the car sector as standard in the 1990s will soon no longer meet the mounting requirements for air hygiene; particulate filters and nitrogen oxide reduction systems, e.g. SCR and storage catalysts, have become standard.

New combustion systems with a larger share of premixed, homogeneous combustion than normal diffusion combustion are just as much the subject of this handbook as the refinement of supercharging to enhance the power output, increase the peak cylinder pressure and thus limit load as the brake mean effective pressure increases. Quickly emerging as the optimal injection system when the car sector switched from indirect to direct injection at the end of the 1990s, the common rail system also came to be used – initially only experimentally – for larger diesel engines at the start of the new millennium. The common rail system is now standard in diesel engines

of virtually every size. Hence, reflecting current but by far not yet finalized development, this handbook treats the different designs, e.g. with solenoid valve-controlled or piezo-actuated injectors, in detail. Ample space has accordingly also been given to electronics with its diverse options to control processes in the engine.

To be able meet the expectations and demands connected with a Handbook of Diesel Engines, we relied as much on the collaboration of outstanding engineers from the engine industry as on the research findings of professors at universities of applied sciences and universities. After all, a particularly close connection has existed between theory and practice, between academia and industry, in engine research since Diesel's day, his invention itself being based on the engineering of his day.

Thanks to the work of many generations of engineers, scientists, researchers and professors, the diesel engine continues to be the most cost effective internal combustion engine and has evolved into an advanced high-tech product.

Berlin, Germany,
Magdeburg, Germany
September 2009

We would like to thank all the authors – whether experts working in industry where the utmost dedication is demanded or our colleagues in academia where the days of creative leisure have long since become a thing of the past – for their collaboration, their ready acceptance of our ideas and the many fruitful discussions. We would also like to extend our gratitude to the companies that allowed their employees to work on the side, supported the compilation of texts and master illustrations and provided material. Acknowledgement is also due the many helpers at companies and institutes for their contributions without which such an extensive book manuscript could never have been produced.

Particularly special thanks go to the Diesel Systems Division at Robert Bosch GmbH for the technical and financial support, which made it possible to complete this extensive work in the first place.

Despite the sometimes hectic pace and considerable additional work, the editors tremendously enjoyed their collaboration with the authors, the publisher and all the other collaborators.

*Klaus Mollenhauer
Helmut Tschoeke*

My engine continues to make great advances. . . . (From Rudolf Diesel's letter of July 3, 1895 to his wife.)

Contents

Contributors	IX	5.2 Injection Nozzles and Nozzle Holders	129
Part I The Diesel Engine Cycle	1	5.3 Injection Systems	137
1 History and Fundamental Principles of the Diesel Engine (<i>Klaus Mollenhauer and Klaus Schreiner</i>)	3	5.4 Injection System Metrology	170
1.1 The History of the Diesel Engine	3	Literature	173
1.2 Fundamentals of Engine Engineering	7	Further Literature	173
1.3 Combustion Cycle Simulation	18	Further Literature on Section 5.2	174
Literature	29	6 Fuel Injection System Control Systems (<i>Ulrich Projahn, Helmut Randoll, Erich Biermann, Jörg Brückner, Karsten Funk, Thomas Küttner, Walter Lehle, and Joachim Zuern</i>)	175
2 Gas Exchange and Supercharging (<i>Helmut Pucher</i>)	31	6.1 Mechanical Control	175
2.1 Gas Exchange	31	6.2 Electronic Control	176
2.2 Diesel Engine Supercharging	38	6.3 Sensors	184
2.3 Programmed Gas Exchange Simulation	56	6.4 Diagnostics	186
Literature	59	6.5 Application Engineering	189
3 Diesel Engine Combustion (<i>Klaus B. Binder</i>)	61	Literature	191
3.1 Mixture Formation and Combustion	61	Further Literature	191
3.2 Design Features	69	Part II Diesel Engine Engineering	193
3.3 Alternative Combustion Processes	73	7 Engine Component Loading (<i>Dietmar Pinkernell and Michael Bargende</i>)	195
3.4 Process Simulation of Injection Characteristic and Rate of Heat Release	74	7.1 Mechanical and Thermal Loading of Components	195
Literature	75	7.2 Heat Transfer and Thermal Loads in Engines	202
4 Fuels (<i>Gerd Hagenow, Klaus Reders, Hanns-Erhard Heinze, Wolfgang Steiger, Detlef Zigan, and Dirk Mooser</i>)	77	Literature	217
4.1 Automotive Diesel Fuels	77	Further Literature	219
4.2 Alternative Fuels	94	8 Crankshaft Assembly Design, Mechanics and Loading (<i>Eduard Köhler, Eckhart Schopf, and Uwe Mohr</i>)	221
4.3 Operation of Marine and Stationary Engines with Heavy Fuel Oil	103	8.1 Designs and Mechanical Properties of Crankshaft Assemblies	221
4.4 Fuel Gases and Gas Engines	114	8.2 Crankshaft Assembly Loading	228
Literature	124	8.3 Balancing of Crankshaft Assembly Masses	236
5 Fuel Injection Systems (<i>Walter Egler, Rolf Jürgen Giersch, Friedrich Boecking, Jürgen Hammer, Jaroslav Hlousek, Patrick Mattes, Ulrich Projahn, Winfried Urner, and Björn Janetzky</i>)	127	8.4 Torsional Crankshaft Assembly Vibrations	250
5.1 Injection Hydraulics	127	8.5 Bearings and Bearing Materials	259
		8.6 Piston, Piston Rings and Piston Pins	270
		Literature	287
		Further Literature	290

9 Engine Cooling (<i>Klaus Mollenhauer and Jochen Eitel</i>)	291	15.2 Emission Control Legislation	426
9.1 Internal Engine Cooling	291	15.3 Pollutants and Their Production	443
9.2 External Engine Cooling Systems	309	15.4 In-Engine Measures for Pollutant Reduction	449
Literature	336	15.5 Exhaust Gas Aftertreatment	455
10 Materials and Their Selection (<i>Johannes Betz</i>)	339	15.6 Emissions Testing	469
10.1 The Importance of Materials for Diesel Engines	339	Literature	483
10.2 Technical Materials for Engine Components	339	Further Literature	485
10.3 Factors for Material Selection	348	16 Diesel Engine Noise Emission (<i>Bruno M. Spessert and Hans A. Kochanowski</i>)	487
10.4 Service Life Concepts and Material Data	348	16.1 Fundamentals of Acoustics	487
10.5 Service Life Enhancing Processes	349	16.2 Development of Engine Noise Emission	487
10.6 Trends in Development	352	16.3 Engine Surface Noise	489
Literature	354	16.4 Aerodynamic Engine Noises	498
Further Literature	355	16.5 Noise Reduction by Encapsulation	499
Part III Diesel Engine Operation	357	16.6 Engine Soundproofing	502
11 Lubricants and the Lubrication System (<i>Hubert Schwarze</i>)	359	Literature	502
11.1 Lubricants	359	Part V Implemented Diesel Engines	505
11.2 Lubrication Systems	370	17 Vehicle Diesel Engines (<i>Fritz Steinparzer, Klaus Blumensaat, Georg Paehr, Wolfgang Held, and Christoph Teetz</i>)	507
Literature	376	17.1 Diesel Engines for Passenger Cars	507
12 Start and Ignition Assist Systems (<i>Wolfgang Dressler and Stephan Ernst</i>)	377	17.2 Diesel Engines for Light Duty Commercial Vehicles	521
12.1 Conditions for the Auto-Ignition of Fuel	377	17.3 Diesel Engines for Heavy Duty Commercial Vehicles and Buses	528
12.2 Fuel Ignition Aids	378	17.4 High Speed High Performance Diesel Engines	544
12.3 Start and Ignition Assist Systems	379	Literature	556
12.4 Cold Start, Cold Running Performance and Cold Running Emissions for Cars	383	Further Literature	557
12.5 Conclusion	386	18 Industrial and Marine Engines (<i>Günter Kampichler, Heiner Bülte, Franz Koch, and Klaus Heim</i>)	559
Literature	386	18.1 Small Single Cylinder Diesel Engines	559
Further Literature	386	18.2 Stationary and Industrial Engines	568
13 Intake and Exhaust Systems (<i>Oswald Parr, Jan Krüger, and Leonhard Vilser</i>)	387	18.3 Medium Speed Four-Stroke Diesel Engines	576
13.1 Air Cleaners	387	18.4 Two-Stroke Low Speed Diesel Engines	592
13.2 Exhaust Systems	393	Literature	607
Literature	398	Standards and Guidelines for Internal Combustion Engines	609
Further Literature	399	Index	621
14 Exhaust Heat Recovery (<i>Franz Hirschbichler</i>)	401		
14.1 Basics of Waste Heat Recovery	401		
14.2 Options of Waste Heat Recovery	404		
Literature	413		
Part IV Environmental Pollution by Diesel Engines	415		
15 Diesel Engine Exhaust Emissions (<i>Helmut Tschoeke, Andreas Graf, Jürgen Stein, Michael Krüger, Johannes Schaller, Norbert Breuer, Kurt Engeljehringler, and Wolfgang Schindler</i>)	417		
15.1 General Background	417		

Contributors

- Michael Bargende*, Prof. Dr.-Ing., Universität Stuttgart, Stuttgart, Germany, michael.bargende@ivk.uni-stuttgart.de
- Johannes Betz*, MTU Friedrichshafen GmbH, Friedrichshafen, Germany, johannes.betz@mtu-online.com
- Erich Biermann*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, erich.biermann@de.bosch.com
- Klaus B. Binder*, Prof. Dr.-Ing., Deizisau, Germany, klaus.b.binder@t-online.de
- Klaus Blumensaat*, Volkswagen AG, Wolfsburg, Germany, klaus.blumensaat@volkswagen.de
- Friedrich Boecking*, Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, friedrich.boecking@de.bosch.com
- Norbert Breuer*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, norbert.breuer@de.bosch.com
- Jörg Brückner*, Dr., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, joerg.brueckner@de.bosch.com
- Heiner Bülte*, Dr.-Ing., Deutz AG, Köln, Germany, buelte.h@deutz.com
- Wolfgang Dressler*, Dr., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, wolfgang.dressler@de.bosch.com
- Walter Egler*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, walter.egler@de.bosch.com
- Jochen Eitel*, Behr GmbH & Co. KG, Stuttgart, Germany, jochen.eitel@behrgroup.com
- Kurt Engeljehring*, AVL List GmbH, Graz, Austria, kurt.engeljehring@avl.com
- Stephan Ernst*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, stephan.ernst@de.bosch.com
- Karsten Funk*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, karsten.funk@de.bosch.com
- Rolf Jürgen Giersch*, Dipl.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, juergen.giersch@de.bosch.com
- Andreas Graf*, Dipl.-Ing., Daimler AG, Stuttgart, Germany, andreas.g.graf@daimler.com
- Gerd Hagenow*, Dr., Shell Global Solutions (Deutschland) GmbH, Hamburg, Germany
- Jürgen Hammer*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, juergen.hammer@de.bosch.com
- Klaus Heim*, Wärtsilä Switzerland Ltd, Winterthur, Switzerland, klaus.heim@wartsila.com
- Hanns-Erhard Heinze*, Dr.-Ing., Magdeburg, Germany, cheheinze@gmx.de
- Wolfgang Held*, Dr.-Ing., MAN Nutzfahrzeuge AG, Nürnberg, Germany, wolfgang.held@man.eu
- Franz Hirschbichler*, Dr., München, Germany, franz.hirschbichler@gmx.de
- Jaroslav Hlousek*, Dipl.-Ing., KEFICO Co, Gunpo, Korea (RoK), jaroslav.hlousek@kr.bosch.com
- Björn Janetzky*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, bjoern.janetzky@de.bosch.com
- Günter Kampichler*, Dipl.-Ing., Ruhstorf, Germany
- Franz Koch*, Dr.-Ing., MAN Diesel & Turbo SE, Augsburg, Germany, franz.koch@man.eu
- Hans A. Kochanowski*, Dr.-Ing., Ruhstorf, Germany
- Eduard Köhler*, Prof. Dr.-Ing. habil., KS Aluminium Technologie GmbH, Neckarsulm, Germany, eduard.koehler@de.kspg.com
- Jan Krüger*, Dr.-Ing., J. Eberspächer GmbH & Co. KG, Esslingen, Germany, jan.krueger@eberspaecher.com
- Michael Krüger*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, michael.krueger2@de.bosch.com
- Thomas Küttner*, Dipl.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, thomas.kuettner@de.bosch.com
- Walter Lehle*, Dr. rer. nat., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, walter.lehle@de.bosch.com
- Patrick Mattes*, Dr., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, patrick.mattes@de.bosch.com
- Uwe Mohr*, Dr., Mahle GmbH, Stuttgart, Germany, uwe.mohr@mahle.com
- Klaus Mollenhauer*, Prof. Dr.-Ing., Berlin, Germany, klamoll@aol.com
- Dirk Mooser*, Dr.-Ing., Caterpillar Motoren GmbH & Co. KG, Kiel, Germany, mooser_dirk@CAT.com
- Georg Paehr*, Dr., Volkswagen AG, Wolfsburg, Germany, georg.paehr@volkswagen.de
- Oswald Parr*, Dr.-Ing., Ludwigsburg, Germany
- Dietmar Pinkernell*, MAN Diesel & Turbo SE, Augsburg, Germany
- Ulrich Projahn*, Dr.-Ing., Robert Bosch GmbH, Diesel Systems, Stuttgart, Germany, ulrich.projahn@de.bosch.com