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Simulating Combustion

Simulation of combustion and pollutant formation for engine-development

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with 242 figures

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Library of Congress Control Number: 2005933399

ISBN 10 3-540-25161-8 Berlin Heidelberg New York
ISBN 13 978-3-540-25161-3 Berlin Heidelberg New York

Originally published as
Günter P. Merker/Christian Schwarz/Gunnar Stiesch/Frank Otto:
Verbrennungsmotoren. Simulation der Verbrennung und Schadstoffbildung

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springeronline.com

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Printed in Germany

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Cover design: medionet AG, Berlin
Typesetting: Digital data supplied by editors

Printed on acid-free paper 68/3020/m-5 4 3 2 1 0

Preface

The numerical simulation of combustion processes in internal combustion engines, including also the formation of pollutants, has become increasingly important in the recent years, and today the simulation of those processes has already become an indispensable tool when developing new combustion concepts. While pure thermodynamic models are well-established tools that are in use for the simulation of the transient behavior of complex systems for a long time, the phenomenological models have become more important in the recent years and have also been implemented in these simulation programs. In contrast to this, the three-dimensional simulation of in-cylinder combustion, i.e. the detailed, integrated and continuous simulation of the process chain injection, mixture formation, ignition, heat release due to combustion and formation of pollutants, has been significantly improved, but there is still a number of challenging problems to solve, regarding for example the exact description of sub-processes like the structure of turbulence during combustion as well as the appropriate choice of the numerical grid.

While chapter 2 includes a short introduction of functionality and operating modes of internal combustion engines, the basics of kinetic reactions are presented in chapter 3. In chapter 4 the physical and chemical processes taking place in the combustion chamber are described. Chapter 5 is about phenomenological multi-zone models, and in chapter 6 the formation of pollutants is described. In chapter 7 and chapter 8 simple thermodynamic models and more complex models for transient systems analyses are presented. Chapter 9 is about the three-dimensional simulation of combustion processes in engines.

We would like to thank Dr. B. Settmacher for reviewing and formatting the text, for preparing the layout, and for preparing the printable manuscript. Only due to her unremitting dedication and her excellent time management the preparation of this book has been possible in the given timeframe. Further on, we would also like to thank Mrs. C. Brauer for preparing all the figures and diagrams contained in this book. The BMW group and the DaimlerChrysler AG contributed to this book by releasing the figures they provided. Last but not least, we would like to thank the Springer-Verlag for the always excellent collaboration.

This book is largely a translation of the second German edition, which has been published in 2004 by the B.G. Teubner-Verlag, whereas the text has been updated if necessary. We would like to thank Mr. Aaron Kuchle for translating the text into English.

Hannover/München/Friedrichshafen/Stuttgart, July 2005

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Abbreviations

50 mfb	50 % mass fraction burned
bb	blow-by
BDC	bottom dead center
BTDC	before top dead center
CA	crank angle
CAC	charge air cooler
CAI	controlled auto-ignition
cc	combustion chamber
CD	combustion duration
CCBDC	charge change bottom dead center
CCTDC	charge change top dead center
CFD	computational fluid dynamics
DI	direct injection
DISI	direct injection spark ignition
DS	delivery start
dv	dump valve
eb	engine block
EGR	exhaust gas recirculation
EV	exhaust valve
EVC	exhaust valve close
EVO	exhaust valve open
EIVC	early intake valve close
FEM	finite element method
HCCI	homogeneous charge compression ignition
hrr	heat release rate
ID	injection duration
IGD	ignition delay
IND	injection delay
ip	injection pump
IP	injection process
IT	ignition time
ITDC	ignition top dead center
IV	intake valve
IVC	intake valve close
IVO	intake valve open
LES	large-eddy-simulation
LIVC	late intake valve close
mcp	mass conversion point
mfb	mass fraction burned
nn	neuronal network
oc	oil cooler
OHC-equ.	oxygen-hydrogen-carbon-equilibrium
op	oil pan

PAH	polycyclic aromatic hydrocarbons
PDF	probability density function
rg	residual gas
SOC	start of combustion
SOI	start of injection
TC	turbocharging, turbocharger
TDC	top dead center
tv	throttle valve
VTG	variable turbine geometry

Symbols

A	surface [m^2]
	kinematics of the Bolzmann equation variable α
	parameter Zacharias
	temperature difference Heider [K]
A^*	temperature difference Heider [K]
A_{id}	ignition model parameter
A_{prem}	combustion model parameter
a	Vibe heat release rate constant
	sonic speed [m / s]
	thermal diffusivity [m^2 / s]
	gradient „crooked coordinates"
	parameter knocking criterion
	reference opening path thermostat
B	function Heider
B_0, B_1	breakup model constants
b	breadth [m]
	parameter knocking criterion
b_e	specific fuel consumption [g / kWh]
C	function Lax Wendroff
	constant
	heat transfer Woschni constant
C_1	Woschni constant
C_2	Woschni constant [m / (s K)]
C_3	Vogel constant
	constant of the particle path
C_4	constant of the particle path
C_A	contraction coefficient
C_{gl}	Heider constant
C_v	velocity coefficient
C_w	drag coefficient
CD	combustion duration [Grad]
Cou	Courant number

c	carbon component [kg / kg fuel]
	spring rate [N / m]
	progress variable
	velocity [m / s]
	constant
	length [m]
	parameter knocking criterion
	specific heat [J / (kg K)]
$c_{(i)}$	species mass fraction of the species no. i
ci	stock concentration
c_f	constant friction method fan
c_m	medium piston velocity [m / s]
c_p	piston velocity [m / s]
	specific heat at constant pressure [J / (kg K)]
c_u / c_m	swirl number
c_x	mixture fraction variance transport equation model constants
$c_{\varepsilon_1}, c_{\varepsilon_2}, c_{\varepsilon_3}$	ε -equation model constants
c_μ	turbulence model constant
c_v	specific heat at constant volume [J / (kg K)]
D	diffusion constant
	diameter [m]
	parameter Zacharias
	cylinder diameter [m]
D_R	inverse relaxation time scale of a drop in turbulent flow [s^{-1}]
$\frac{\partial}{\partial t}$	partial differential
d	wall thickness [m]
	diameter [m]
	damping factor [kg / s]
d_f	fan diameter [m]
d_m	medium turbine diameter [m]
E	energy [J]
$\dot{E}$	energy flow [J / s]
E_A	activation energy
E_{id}	ignition energy [K]
E_{kin}	kinetic spray energy [J]
EB	energy balance
EGR	exhaust gas recirculation [%]
e	eccentricity, crossing [m]
F	Lax Wendroff function
	flexibility of the engine [Nm s]
	force [N]
	function
F_g	gas force [N]
FA	parameter Zacharias

f	general function
	force density [N/m^3]
	distribution function
f_{rg}	mass fraction of the residual gas
$fmep$	mean friction pressure [bar]
G	formal field variable, which zeros localize the flame front position
	free enthalpy [J]
	function Lax Wendroff
	Gibbs function [J]
g	specific free enthalpy [J / kg]
H	enthalpy [J]
	heating value [J / kg]
h	hydrogen component [kg / kg Kst]
	specific enthalpy [J / kg]
	stroke [m]
h_1	parameter polygon hyperbolic heat release rate
h_2	parameter polygon hyperbolic heat release rate
h_3	parameter polygon hyperbolic heat release rate
I	impulse [(kg m) / s]
	current [A]
I_K	knocking initiating critical pre reaction level
ID	injection duration [Grad]
ifa	fan ratio
$imep$	indicated mean effective pressure [N / m^2]
iz	number of line sections
L	angular momentum [N m s]
	length scale [m]
K	combustion chamber dependent constant (Franzke)
K_d	differential coefficient
K_i	integral coefficient
K_p	proportional coefficient
	equilibrium constant
K_b	bearing friction constant
K_η	constant [m^3]
K_ρ	factor gap thickness
k	constant
	turbulent kinetic energy [m^2 / s^2]
	heat transfer coefficient [$W / (m^2 K)$]
	index
k_c	container stiffness [N / m^5]
k_f	velocity coefficient for the forward reaction
	pipe friction coefficient [m / s^2]
k_r	velocity coefficient for the reverse reaction
kp	knocking probability
L	swirl length [m]