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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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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.

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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]

$L_{\min}$	minimal air requirement (stoichiometric combustion)
l	connecting rod length [m]
	length [m]
l_F	thickness of the turbulent flame front [m]
l_I	integral length scale
l_t	turbulent length scale [m]
lhv	lower heating value [J / kg]
M	mass [kg]
	molar mass [kg / kmol]
Ma	Mach number
m	mass [kg]
	Vibe parameter
$\dot{m}$	mass flow
mep	mean effective pressure [N / m^2]
N	normalization constant
Nu	Nußelt number
n	number of moles
	polytrope exponent
	speed [rpm]
n_i	quantity of substance [mol]
n_{wc}	number of working cycles per time
Oh	Ohnesorge number
P	power [W]
	term of production in k-equation [W]
Pe	Peclet number
Pr	Prandtl number
Pr_k	turbulent Prandtl number for k transport
Pr_ε	turbulent Prandtl number for ε transport
p	partial pressure [N / m^2]
	pressure [N / m^2]
	probability density, distribution function
p_0	pressure of the motored engine [N / m^2]
p_{Gauss}	distribution function with Gaussian distribution
p_{inj}	injection pressure [N / m^2]
p_β	distribution function with β-function distribution
Q	source term of a scalar transport equation
	amount of heat [J]
$\dot{Q}$	heat flow [W]
Q_f, Q_{chem}	heat release [kJ / KW]
q	specific heat [J / m^3]
	heat source [W]
R	electrical resistance [Ohm;Ω]
	gas constant [J / (kg K)]
	drop radius [m]
$\widetilde{R}$	universal gas constant

R_0	universal gas constant [J / (mol K)]
$\dot{R}_{dis}$	drop radius change because of disintegration [m / s]
$\dot{R}_{evap}$	drop radius change because of evaporation [m / s]
R_m	molar gas constant [J / (mol K)]
R_{th}	thermal substitute conduction coefficient [W / (m^2 K)]
Re	Reynolds number
r	crankshaft radius [m]
	air content
	radius [m]
S	entropy [J / K]
	spray penetration [m]
S_{ij}	shear tensor [s^{-1}]
Sc	Schmidt number
SF	scavenging factor
Sh	Sherwood number
SMD	Sauter mean diameter [m]
s	flame speed [m / s]
	piston path, stroke [m]
	specific entropy [J / (kg K)]
s_b	bowl depth [m]
s_L	laminar flame speed [m / s]
s_t	turbulent flame speed [m / s]
T	Taylor number
	temperature [K]
	Torque [Nm]
$\dot{T}_{heat}$	drop temperature change because of heating [K / s]
t	time [s]
U	internal energy [J]
u	specific internal energy [J / kg]
	velocity component [m / s]
u'	turbulent velocity fluctuation [m / s]
u / c_0	type number
V	length scale [m / s]
	volume [m^3]
V_d	displacement (cubic capacity) [m^3]
v	velocity [m / s]
	specific volume [m^3 / kg]
v^+	standardized velocity (turbulent wall law)
v_{inj}	injection velocity [m / s]
v_τ	shear stress velocity [m / s]
W	work [J]
$\dot{W}$	power [W]
We	Weber number
w	velocity [m / s]
	specific work [J / kg]

w_i	indicated work [kJ / l]
X	control variable
Y	correcting variable
X_d	control deviation
x	component
	coordinate
	distance [m]
	random number
x_{rg}	amount of residual gas
y	coordinate
	component
y^+_*	standardized wall distance (turbulent wall law)
y_2	parameter polygon hyperbole heat release rate
y_4	parameter polygon hyperbole heat release rate
y_6	parameter polygon hyperbole heat release rate
z	component
	coordinate
	mixture fraction
	number of cylinders
	random number

Greek symbols

α	generic parameter
	flow coefficient
	coefficient Lax Wendroff
	variable set of the spray adapted Boltzmann equation
	heat transfer coefficient [W / (m^2 K)]
a_F	model parameter of the flame surface combustion model
β	generic parameter
	coefficient Lax Wendroff
	reduced variable set of the spray adapted Boltzmann equation
	angle [°]
β_F	model parameter of the flame surface combustion model
γ	angle [°]
Δ	difference
	combustion term
Δ_m	Vibe parameter
Δt	time increment [s]
Δx	length increment [m]
$\Delta\eta$	efficiency difference
$\Delta\phi$	combustion duration [Grad]
δ_0	thickness of the laminar flame front [m]
ε	dissipation rate [m^2 / s^2]

	cooling coefficient
	compression ratio
Γ	Gamma function
	ITNFS function (premix combustion model)
η_{th}	thermal efficiency
η	dynamic viscosity [$(\mathrm{N\ s}) \,/\, \mathrm{m}^2$]
η_{conv}	degree of conversion
Θ	polar mass moment of inertia [$\mathrm{kg} / \mathrm{m}^2$]
ϑ	temperature [K]
κ	isentropic exponent
	von Karman constant (turbulence model)
Λ	wavelength in droplet breakup model [m]
λ	air-fuel ratio
	heat conductivity [W / (m K)]
λ^*	mixture stoichiometry
λ_0	air-fuel ratio Heider
λ_L	volumetric efficiency
λ_a	air expenditure
λ_e	eccentric rod relation
λ_f	pipe friction coefficient
μ	chemical potential
	flow coefficient
	1st viscosity coefficient (without index: laminar) [$(\mathrm{N\ s}) \,/\, \mathrm{m}^2$]
ν	kinematic viscosity [$\mathrm{m}^2 \,/\, \mathrm{s}$]
	amount of substance [mol]
ν_i	stoichiometric coefficient
Π_{br}	branch pressure ratio
π	pressure ratio
	mathematical constant (3,14159)
π_t^*	reciprocal value turbine pressure ratio
π_c	compressor pressure ratio
ρ	density [$\mathrm{kg} \,/\, \mathrm{m}^3$]
σ	specific flame front [$\mathrm{m}^2 \,/\, \mathrm{kg}$]
	transient function in Boltzmann equation
	variance
τ	time of flight [s]
	stress (also tensor) [$\mathrm{N} \,/\, \mathrm{m}^2$]
	time (ignition delay) [s]
τ_{corr}	correlation time of the velocity fluctuation affecting a drop [s]
τ_{id}	ignition delay [s]
τ_{trb}	turbulent time scale
Φ	generic transport variable
	ratio of equivalence
	specific cooling capacity [W / K]
ξ	part

	2nd laminar viscosity coefficient [$(\mathrm{N\ s}) \,/\, \mathrm{m}^2$]
φ	crankshaft angle [°KW]
Ψ	outflow function
ψ	relative clearance of a bearing [m]
Ω	growth rate of the wavelength Λ in droplet breakup model [s^{-1}]
ω	angular speed [s^{-1}]
	swirl number
ζ	pipe friction number

Operators

$\langle\ \rangle$	ensemble averaging
$\langle\ \rangle_F$	Favre averaging
$'$	fluctuation in ensemble average
$''$	fluctuation in Favre average

Indices

*	dimensionless quantity
$\dot{}$	time differentiation
$\bar{}$	molar quantity
$^\circ$	reference pressure 1 atm.
	standard status
$\sim$	molar quantities
0	idle condition
	drag
	index Runge Kutta
01	idle condition
1	supplied
	after throttling device
	before flow machine
	zone 1
	index Runge Kutta
	when inlet closes
	constant friction
1′	base
15	at 15°C
2	removed
	after flow machine
	zone 2
	index Runge Kutta
	constant friction

$2'$	base
3	index Runge Kutta
	constant friction
4	constant friction
5	constant friction
6	constant friction
$50\,mfb$	50 % mass fraction burned
75	at 75% conversion rate
$(i), (j), (k)$	number of species
A	starting point
	branch A
a	axial
$a.\,c.$	after compressor
$a.\,t.$	after turbine
act	actual
add	added
B	branch B
BDC	bottom dead center
b	bearing
	burned
$b.\,c.$	before compressor
$b.\,comb.$	before combustion
$b.\,t.$	before turbine
bb	blow-by
C	carbon
	crankshaft
C_3H_8	propane
CAC	charge air cooler
CD	combustion duration
CO	carbon monoxide
CO_2	carbon dioxide
c	Carnot process
	circumference
	compression, compressor
	cooler
c, $conv$	conversion
c, $cyl.$	cylinder
$c.p.$	crank pin
$c.r.$	connecting rod
ch, $chem$	chemical
cm	cooling mass
$comp$	compression
$corr$	correction, corrected
cs	calculation start

cyl	cylinder
cylw	cylinder wall
DS	delivery start
diff.	diffusion
dr	drop, droplet
dx	length increment
E	exhaust gas
	end gas, characteristic crank angle knocking criterion
EOC	end of combustion
evap	evaporated
EVO	exhaust valve open
e	effective
eg	exhaust gas
env	environment
F	flame, flame front
f	foot (point)
	formation
	friction
	fuel
fg	gaseous fuel
	fresh gas
fl	liquid fuel
Gl	glysantin
g	gas
	gas phase
gl	global
H_2	hydrogen
H_2O	water
ID	injection duration
IND	injection delay
IGD	ignition delay
IT	ignition time
IV	intake valve
IVC	intake valve close
IK	initiating knocking
i	index
	inlet
	inner, inside
id	inflammation duration
imp	imperfect
ind	indicated
inj	injected, injection
is	isentropic
j	index
K	knocking, characteristic crank angle knocking criterion

kpr	knocking probability region
krit.	critical
L	line
l	lower
l, *lam*	laminar
m	mass
	mechanic
	medium
	molar
max	maximal
min	minimal
N_2	nitrogen
n	speed
	component C
noz	nozzle
o	outer
	out, outlet
	standard state
osc	oscillated
p	constant pressure process
	(constant) pressure
p	packet
	piston
pre	premixed
r	radial
ref	reference
rem, *remov.*	removed
rg	residual gas
rot	rotating
SOC	start of combustion
SOI	start of injection
s	isentropic
	stroke
sc	short circuit
spray	spray adapted
sq	squeeze
suppl	supplied
sys	system
T	tangential
	temperature
	turbine
TC	turbocharger
TDC	top dead center
TG	gas tangential pressure
TM	mass tangential pressure

t	technical
	turbulent
tc	to be cooled
th	thermostat
	thermal
th., theo.	theoretic
tot	total
turb	turbulent
u	upper
u, *ub*	unburned
v	constant-volume process
	specific volume
	competitive process
v_p	Seiliger process
vol	volume
W, *w*	wall
x	point x
	starting point
x_{rg}	residual gas
y	component H
z	component O
	number of cycles
α	convective
ε	radiation

1 Introduction

1.1 Preface

One of the central tasks of engineering sciences is the most possibly exact description of technical processes with the goal of understanding the dynamic behavior of complex systems, of recognizing regularities, and thereby of making possible reliable statements about the future behavior of these systems. With regard to combustion engines as propelling systems for land, water, and air vehicles, for permanent and emergency generating sets, as well as for air conditioning and refrigeration, the analysis of the entire process thus acquires particular importance.

In the case of model-based parameter-optimization, engine behavior is described with a mathematical model. The optimization does not occur in the real engine, but rather in a model, which takes into account all effects relevant for the concrete task of optimization. The advantages of this plan are a drastic reduction of the experimental cost and thus a clear saving of time in developmental tasks, see Kuder and Kruse (2000).

The prerequisite for simulation are mechanical, thermodynamic, and chemical models for the description of technical processes, whereby the understanding of thermodynamics and of chemical reaction kinetics are an essential requirement for the modeling of motor processes.

1.2 Model-building

The first step in numeric simulation consists in the construction of the model describing the technical process. Model-building is understood as a goal-oriented simplification of reality through abstraction. The prerequisite for this is that the real process can be divided into single processual sections and thereby broken down into partial problems. These partial problems must then be physically describable and mathematically formulatable.

A number of demands must be placed upon the resulting model:

- The model must be formally correct, i.e. free of inconsistencies. As regards the question of "true or false", it should be noted that models can indeed be formally correct but still not describe the process to be investigated or not be applicable to it. There are also cases in which the model is physically incorrect but nevertheless describes the process with sufficient exactness, e.g. the Ptolemaic model for the simulation of the dynamics of the solar system, i.e. the calculation of planetary and lunar movement.
- The model must describe reality as exactly as possible, and, furthermore, it must also be mathematically solvable. One should always be aware that every model is an approximation to reality and can therefore never perfectly conform with it.
- The cost necessary for the solution of the model with respect to the calculation time must be justifiable in the context of the setting of the task.
- With regard to model-depth, this demand is applicable: as simple as possible and as complex as necessary. So-called universal models are to be regarded with care.

It is only by means of the concept of model that we are in the position truly to comprehend physical processes.

In the following, we will take a somewhat closer look into the types of models with regard to the combustion engine. It must in the first place be noted that both the actual thermodynamic cycle process (particularly combustion) and the change of load of the engine are unsteady processes. Even if the engine is operated in a particular operating condition (i.e. load and rotational speed are constant), the thermodynamic cycle process runs unsteadily. With this, it becomes obvious that there are two categories of engine models, namely, such that describe the operating condition of the engine (total-process models) and such that describe the actual working process (combustion models).

With respect to types of models, one distinguishes between:

- *linguistic models*, i.e. a rule-based method built upon empirically grounded rules, which cannot be grasped by mathematical equations, and
- *mathematical models*, i.e. a method resting on mathematical formalism.

Linguistic models have become known in recent times under the concepts "expert systems" and "fuzzy-logic models". Yet it should thereby be noted that rule-based methods can only interpolate and not extrapolate. We will not further go into this type of model.

Mathematical models can be subdivided into:

- parametric, and
- non-parametric

models. Parametric models are compact mathematical formalisms for the description of system behavior, which rests upon physical and chemical laws and show only relatively few parameters that are to be experimentally determined. These models are typically described by means of a set of partial or normal differential equations.

Non-parametric models are represented by tables that record the system behavior at specific test input signals. Typical representatives of this type of model are step responses or frequency responses. With the help of suitable mathematical methods, e.g. the Fourier transformation, the behavior of the system can be calculated at any input signal.

Like linguistic models, non-parametric models can only interpolate. Only mathematical models are utilized for the simulation of the motor process. But because the model parameters must be adjusted to experimental values in the case of these models as well, they are fundamentally error-prone. These errors are to be critically evaluated in the analysis of simulation results. Here too, it becomes again clear that every model represents but an approximation of the real system under observation.

1.3 Simulation

For the construction of parametric mathematical models for the simulation of temporally and spatially variable fluid, temperature, and concentration fields with chemical reactions, the knowledge of thermodynamics, fluid dynamics, and of combustion technology is an essential prerequisite, see Fig. 1.1.

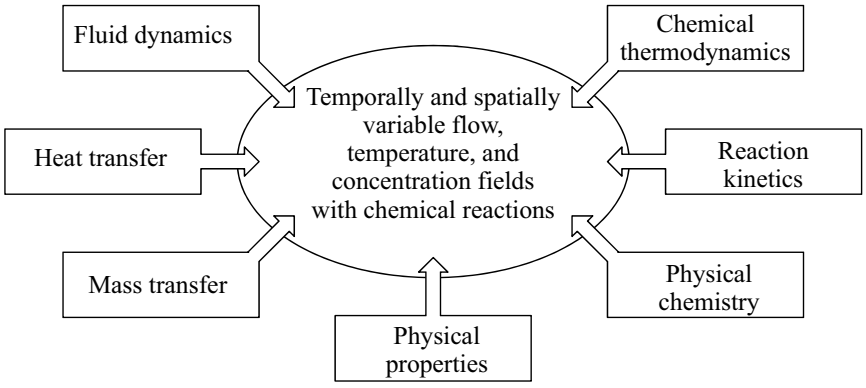

Fig. 1.1: Area of knowledge important for process simulation

With respect to the simulation of fluid fields with chemical reactions, it should be noted that physical and chemical processes can progress at very different temporal and linear scales. The description of these process progressions is usually simpler when the time scales are much different, because then simplifying assumptions can be made for the chemical or physical process, and it is principally very complex when the time scales are of the same order of magnitude. This is made clear by means of the examples in Fig. 1.2.

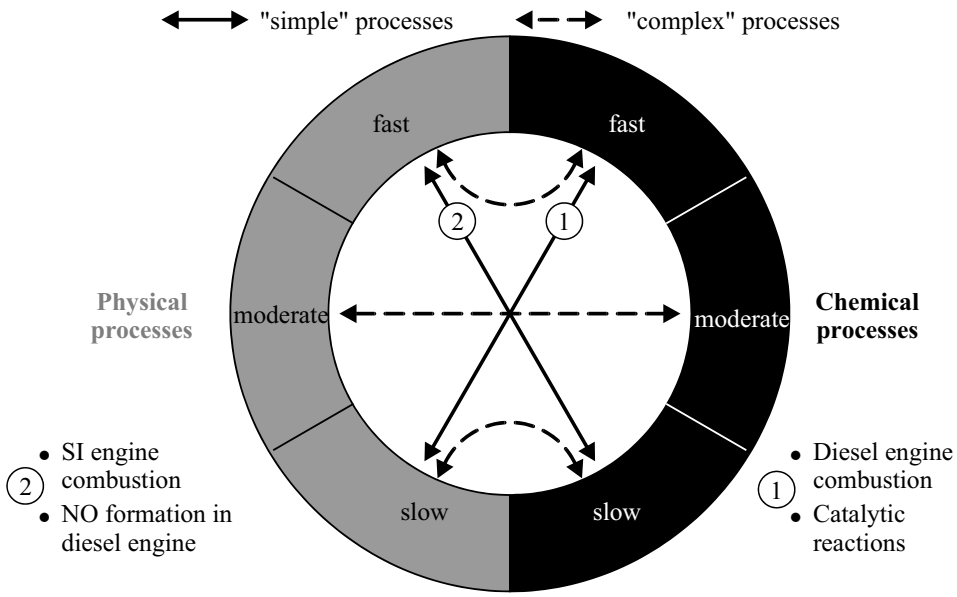

Fig. 1.2: Time scales of physical and chemical processes influencing process simulation

Yet in addition, knowledge of modeling methods is also necessary. Although some universally valid rules can be given for this, this step allows a lot of free room for the creativity and imagination of the modeler. Essentially, the modeling procedure can be subdivided into the following steps:

1st step: define the system and boundaries from the environment, determine the relevant reservoirs as well as the mass and energy flow between them.

2nd step: draw up balance sheets according to the unified scheme: temporal change of the reservoir is equal to the inflow minus the outflow.

3rd step: with the help of physical laws, describe the mass and energy flows.

4th step: simplify the resulting model, if necessary by neglecting secondary influences.

5th step: integrate the model numerically, i.e. execute the simulation.

6th step: validate the model, compare the calculated data with experimentally obtained data.

In the utilization of an existing simulation program for the solution of new tasks, the prerequisites which were met in the creation of the model must always be examined. It should thereby be clarified whether and to what extent the existing program is actually suitable for the solution of the new problem. One should in such cases always be aware of the fact that "pretty, colorful pictures" exert an enormous power of suggestion upon the "uncritical" observer.

The prerequisite for the acceptance of what we nowadays designate as computer simulation was a gradual alteration in philosophical thought and in the conceptualization and understanding of the world in which we live. In the past, humanity perceived the world and its processes predominately as linear and causal, and we are gradually comprehending the decisive processes flow in a non-linear and chaotic fashion. Only with the rise of the sciences and with the development of their methodological foundations could the basis for computer simulation be created.

Numeric simulation opens up unimagined possibilities. We can get an idea of what is to be expected in this field if we bear in mind the rapid development in the information sector and compare the present condition of "email" and the "internet" with that of ten years past.

With respect to technological progress and the ecological perspectives related to it, the reader is referred to Jischa (1993). Also, Kaufmann and Smarr (1994) have provided interesting insight into the topic of simulation.

2 Introduction into the functioning of internal combustion engines

2.1 Energy conversion

In energy conversion, we can distinguish hierarchically between general, thermal, and motor energy conversion.

Under *general energy* conversion is understood the transformation of primary into secondary energy through a technical process in an energy conversion plant, see Fig. 2.1.

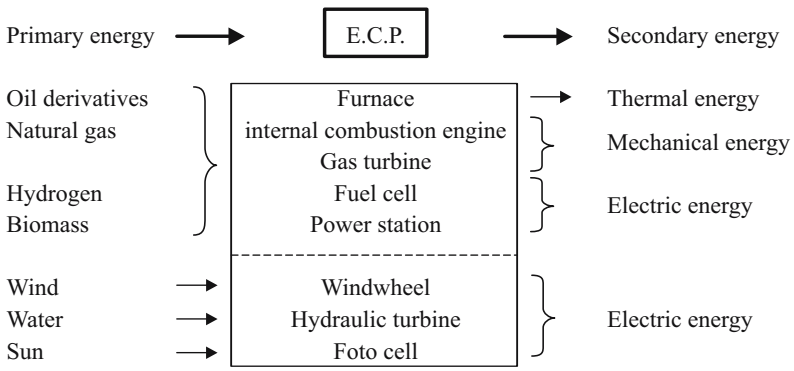

Fig. 2.1: Diagram of general energy conversion

Thermal energy conversion is subject to the laws of thermodynamics and can be described formally, as is shown in Fig. 2.2.

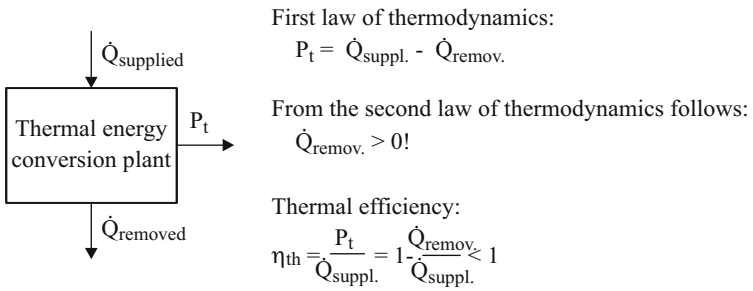

Fig. 2.2: Diagram of thermal energy conversion

The *internal combustion engine* and the *gas turbine* are specialized energy conversion plants, in which the chemical energy bound in the fuel is at first transformed into thermal energy in

the combustion space or chamber, this being then transformed into mechanical energy by the motor. In the case of the stationary gas turbine plant, the mechanical energy is then converted into electrical energy by the secondary generator.

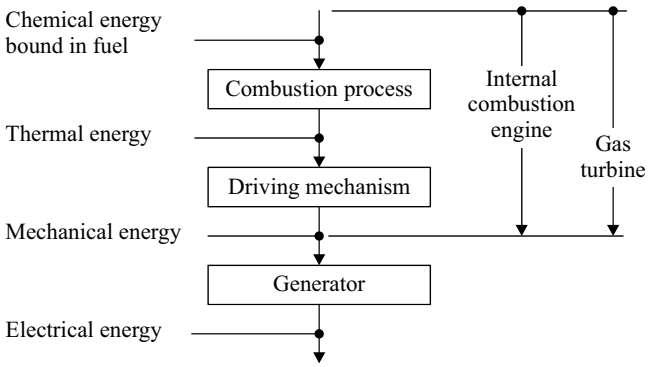

Fig. 2.3: Diagram of energy conversion in an internal combustion engine or gas turbine

2.2 Reciprocating engines

Internal combustion engines are piston machines, whereby one distinguishes, according to the design of the combustion space or the pistons, between reciprocating engines and rotary engines with a rotating piston movement. Fig. 2.4 shows principle sketches of possible structural shapes of reciprocating engines, whereby today only variants 1, 2, and 4 are, practically speaking, still being built.

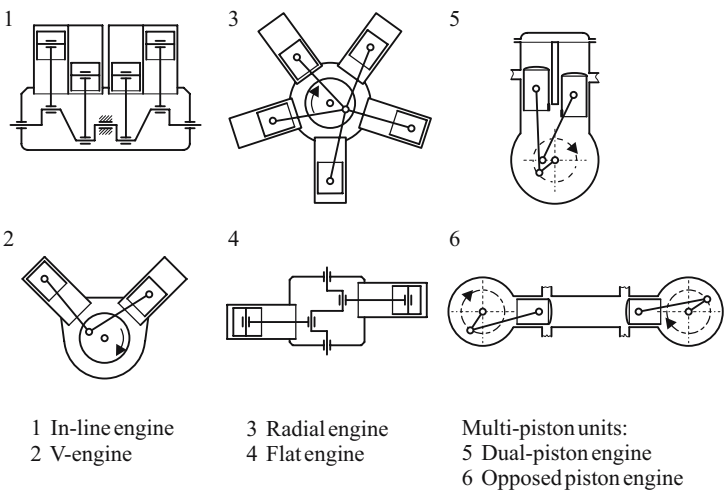

Fig. 2.4: Types of reciprocating engines

For an extensive description of other models of the combustion engine, see Basshuysen and Schäfer (2003) and Maas (1979).

2.2.1 The crankshaft drive

The motor transforms the oscillating movement of the piston into the rotating movement of the crankshaft, see Fig. 2.5. The piston reverses its movement at the top dead center (TDC) and at the bottom dead center (BDC). At both of these dead point positions, the speed of the piston is equal to zero, whilst the acceleration is at the maximum. Between the top dead center and the underside of the cylinder head, the compression volume V_c remains (also the so-called dead space in the case of reciprocating compressors).

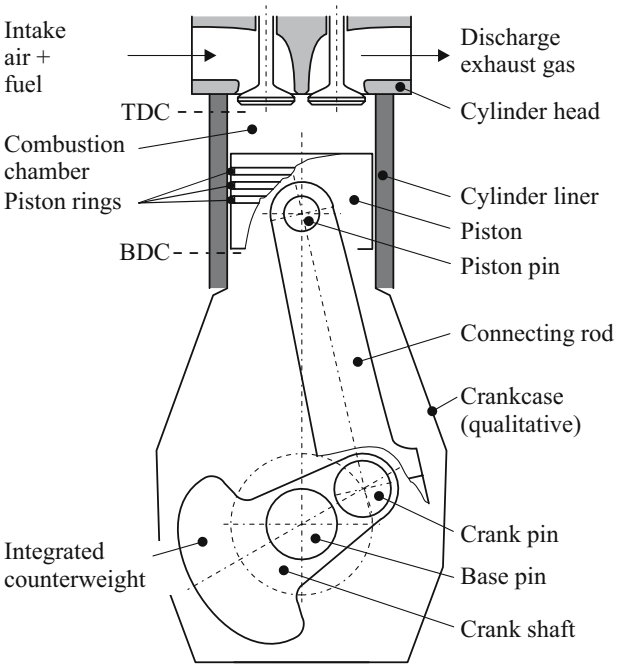

Fig. 2.5: Assembly of the reciprocating engine

Fig. 2.6 shows the kinematics of a crankshaft drive with crossing, in which the longitudinal crankshaft axle does not intersect with the longitudinal cylinder axle, but rather is displaced by the length e.