Heat and Mass Transfer

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Mixture Formation in Internal Combustion Engines

With 180 Figures and 9 Tables

Springer

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Preface

A systematic control of mixture formation with modern high-pressure injection systems enables us to achieve considerable improvements of the combustion process in terms of reduced fuel consumption and engine-out raw emissions. However, because of the growing number of free parameters due to more flexible injection systems, variable valve trains, the application of different combustion concepts within different regions of the engine map, etc., the prediction of spray and mixture formation becomes increasingly complex. For this reason, the optimization of the in-cylinder processes using 3D computational fluid dynamics (CFD) becomes increasingly important.

In these CFD codes, the detailed modeling of spray and mixture formation is a prerequisite for the correct calculation of the subsequent processes like ignition, combustion and formation of emissions. Although such simulation tools can be viewed as standard tools today, the predictive quality of the sub-models is constantly enhanced by a more accurate and detailed modeling of the relevant processes, and by the inclusion of new important mechanisms and effects that come along with the development of new injection systems and have not been considered so far.

In this book the most widely used mathematical models for the simulation of spray and mixture formation in 3D CFD calculations are described and discussed. In order to give the reader an introduction into the complex processes, the book starts with a description of the fundamental mechanisms and categories of fuel injection, spray break-up, and mixture formation in internal combustion engines. They are presented in a comprehensive way using data from experimental investigations. Next, the basic equations needed for the simulation of mixture formation processes are derived and discussed in order to give the reader the basic knowledge needed to understand the theory and to follow the description of the detailed sub-models presented in the following chapters. These chapters include the modeling of primary and secondary spray break-up, droplet drag, droplet collision, wall impingement, and wall film formation, evaporation, ignition, etc. Different modeling approaches are compared and discussed with respect to the theory and underlying assumptions, and examples are given in order to demonstrate the capabilities of today's simulation models as well as their shortcomings. Further on, the influence of the computational grid on the numerical computation of spray processes is discussed. The last chapter is about modern and future mixture formation and combustion processes. It includes a discussion of the potentials and future developments of high-pressure direct injection diesel, gasoline, and homogeneous charge compression ignition engines.

This book may serve both as a graduate level textbook for combustion engineering students and as a reference for professionals employed in the field of combustion engine modeling.

The research necessary to write this book was carried out during my employment as a postdoctoral scientist at the Institute of Technical Combustion (ITV) at the University of Hannover, Germany. The text was accepted in partial fulfillment of the requirements for the postdoctoral Habilitation-degree by the Department of Mechanical Engineering at the University of Hannover.

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Hannover, October 2005 Carsten Baumgarten

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Nomenclature

Abbreviations

ATDC	after top dead center
B	Spalding transfer number
BMEP	break mean effective pressure
BTDC	before top dead center
CAI	controlled auto-ignition
CAN	controlled auto-ignition number
CFD	computational fluid dynamics
CI	compression ignition
CN	cetane number, cavitation number
CR	compression ratio, common rail
DDB	droplet deformation and break-up model
DDM	discrete droplet model
DI	direct injection
DISI	direct injection spark ignition
DNS	direct numerical simulation
EGR	exhaust gas recirculation
GDI	gasoline direct injection
HCCI	homogeneous charge compression ignition
HTO	high temperature oxidation
ICAS	interactive cross-sectionally averaged spray
IMEP	indicated mean effective pressure
K	cavitation number
KH	Kelvin-Helmholtz model
La	Laplace number
LES	large eddy simulation
LHF	lower heating value
LISA	linearized instability sheet atomization model
LTO	low temperature oxidation
M	third body species in chemical reactions
MEF	maximum entropy formalism
MW	molecular weight
NTC	negative temperature coefficient
Nu	Nusselt number

ON	octane number
PDF	probability density function
PFI	port fuel injection
PM	particulate matter (soot)
Pr	Prandtl number
RANS	Reynolds averaged Navier-Stokes equations
Re	Reynolds number
RT	Rayleigh-Taylor model
Sc	Schmidt number
Sh	Sherwood number
SI	spark ignition
SMD	Sauter mean diameter
SOC	start of combustion
SR	swirl ratio
St	Stokes number
T	Taylor number
TAB	Taylor-analogy break-up model
TDC	top dead center
UIS	unit injector system
UPS	unit pump system
VCO	valve covered orifice
VVT	variable valve train
We	Weber number
Z	Ohnesorge number

Symbols

a	sound speed [m/s], acceleration [m^2/s^2], thermal diffusivity [m^2/s], major semi axis of ellipsoid [m]
A	area [m^2], constant [/]
b	minor semi axis of ellipsoid [m], spray width [m]
B	non-dimensional impact parameter [/]
c	molar density, concentration [mol/m^3]
C	constant [/]
C_c	contraction coefficient [/]
C_d	discharge coefficient [/]
C_D	drag coefficient [/]
c_f	wall friction coefficient [/]

c_p	specific heat capacity at constant pressure [J/(kg K)]
c_v	specific heat capacity at constant volume [J/(kg K)]
$\overline{c}_v$	molar specific heat at constant volume [J/mol K]
$\overline{c}_p$	molar specific heat at constant pressure [J/mol K]
d	diameter [m], damping constant [kg/s]
D	nozzle hole diameter [m], blob diameter [m], binary diffusivity [m^2/s]
$\overline{D}, \tilde{D}, \hat{D}$	binary diffusion coefficients (cont. thermodynamics) [m^2/s]
e	specific internal energy [J/kg]
E	energy [J]
f	function, body force [N/m^3]
F	force [N]
h	enthalpy [J/kg], liquid film thickness [m]
h_{f0}	latent heat of vaporization [J/kg]
$\overline{h}_{fg}$	molar heat of vaporization [J/mol]
I	mod. Bessel function of first kind, distribution variable, usually molecular weight [kg/kmol]
J	moment of inertia [kg m^2]
k	wave number [m^{-1}], specific turbulent kinetic energy [J/kg], loss coefficient [/], spring constant [N/m], constant [/], k-factor [μm]
K	wave number of fastest growing wave [m^{-1}], modified Bessel function of second kind, constant [/]
K_C	form loss coefficient [/]
l	length [m]
L	length of nozzle hole [m], angular momentum [(kg m^2)/s]
L_A	atomization length scale [m]
L_t	turbulence length scale [m]
m	mass [kg]
M	momentum [N·m]
n	engine speed [min^{-1}], number, quantity [/]

$\dot{n}$	molar flux [mol/(m^2 s)]
$\vec{n}$	unit vector normal to a surface
N	number, quantity [/]
p	pressure [Pa]
P	probability [/]
$\dot{q}$	heat flux per unit area, [W/m^2], distribution parameter (Rosin-Rammler dist.) [/]
Q	heat, [J]
$\dot{Q}$	heat flux [W]
r	radius [m]
R	radius of bubble or drop [m], gas constant [J/(kg K)]
$\overline{R}$	(universal) molar gas constant [J/(mol K)], $\overline{R} = 8.314151$ J/(mol K)
s	entropy [J/(kg K)]
S	spray penetration length [m]
$\overline{s}_{fg}$	molar entropy of evaporation [J/(mol K)]
S	Shannon entropy [/]
t	time, [s]
T	temperature [K]
T^+	dimensionless temperature [/]
T_b	boiling temperature [K]
u	velocity component, usually in x-direction [m/s]
u_1, u_2, u_3	velocity components in a Cartesian coordinate system [m/s]
U	velocity [m/s]
u^+	non-dimensional velocity [/]
v	velocity component, usually in y-direction [m/s]
V	volume [m^3]
w	velocity component, usually in z-direction [m/s]
W	work [J]
x	coordinate [m], mole fraction in liquid phase [/]
x_1, x_2, x_3	coordinates in a Cartesian system [m]
X	impact parameter [m]
y	coordinate [m], mole fraction in gas phase [/], non-dimensional droplet deformation [/]
y^+	non-dimensional distance from wall [/]
Y	deformation [m], mass fraction in gas phase [/]
z	coordinate [m]

Greek Letters

α	void fraction [/], convection heat transfer coefficient [W/(m^2 K)], spray angle [deg], shape parameter of gamma function [/]
β	shape parameter of gamma function [/], spray angle [deg]
γ	shape parameter of gamma function [/]
Γ	gamma function [/]
δ	thickness [m]
Δ	difference [/], diameter ratio [/]
ε	compression ratio [/], dissipation rate of turbulent kinetic energy [m^2/s^3]
η	efficiency [/], disturbance on gas/liquid interface [m]
θ	spray cone angle [rad], [deg], first moment (mean value) of a distribution
κ	energy ratio [/], adiabatic exponent [/], constant [/]
λ	air-fuel equivalence ratio ($=1/\phi$) [/], wave length [m], thermal conductivity [W/(m K)] Lagrange multiplier (MEF)
Λ	wave length of fastest growing wave [m]
μ	dynamic viscosity [(N s)/m^2]
ν	kinematic viscosity [m^2/s], collision frequency [s^{-1}]
ξ	random number [/]
ρ	density [kg/m^3]
σ	surface tension [N/m], variance of a distribution
τ	characteristic time scale [s], shear stress [N/m^2]
τ_A	atomization time scale [s]
τ_t	turbulence time scale [s]
φ	angle [rad], [deg]
ϕ	fuel-air equivalence ratio [/], spray cone angle [rad], [deg]
Φ	angle [rad], [deg],

	turbulence energy spectrum [/], viscous dissipation [W], dissipation function [W/m^3]
ψ	angle [rad], second moment of a distribution
ω	growth rate [s^{-1}], angular frequency [s^{-1}]
Ω	growth rate of most unstable wave [s^{-1}]

Subscripts and Superscripts

0	reference value, initial condition
∞	condition at infinity or ambient
a	atomization
ad	adiabatic
$aero$	aerodynamic
amb	ambient
av	average
ax	axial
b	break-up
bu	break-up
cav	cavitation
$coll$	collapse, collision
$cond$	conduction
$conv$	convection
$crit$	critical value, at critical point
cs	control surface
cv	control volume
cyl	cylinder
eff	effective
EGR	recycled gas
eq	equilibrium
$evap$	evaporation
f	fuel
g	gas
i	variable index, imaginary part of imaginary number
ign	ignition
imp	impingement
in	incoming
inj	injection

k	variable index, kernel
kin	kinetic
l	liquid, laminar
lam	laminar
m	variable index, model, mass
max	maximum
min	minimum
mix	mixture
n	normal, variable index
osc	oscillation
out	outgoing
pl	plasma
r	radial, real part of imaginary number
R	at radius R
rel	relative
ref	reference
res	resulting, residence
rot	rotation
s	surface, source term, splash, sac hole
sat	saturation
sp	spark
sto	stoichiometric
$surf$	surface
t	turbulent, tangential, total
$turb$	turbulent
u	unburned
vap	vapor
w	wall
σ	surface tension
•	$d(\ )/dt$
••	$d^2(\ )/dt^2$
–	averaged value
→	vector

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