

Heat and Mass Transfer

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Carsten Baumgarten

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)] |
| \bar{c}_v | molar specific heat at constant volume [J/mol K] |
| \bar{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] |
| $\bar{D}, \tilde{D}, \hat{D}$ | 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] |
| \bar{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 [/] |

XIV Nomenclature

| | |
|-----------------|---|
| \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)] |
| \bar{R} | (universal) molar gas constant [J/(mol K)], $\bar{R} = 8.314151$ J/(mol K) |
| s | entropy [J/(kg K)] |
| S | spray penetration length [m] |
| \bar{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/ϕ) [/], 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 |
| <i>a</i> | atomization |
| <i>ad</i> | adiabatic |
| <i>aero</i> | aerodynamic |
| <i>amb</i> | ambient |
| <i>av</i> | average |
| <i>ax</i> | axial |
| <i>b</i> | break-up |
| <i>bu</i> | break-up |
| <i>cav</i> | cavitation |
| <i>coll</i> | collapse, collision |
| <i>cond</i> | conduction |
| <i>conv</i> | convection |
| <i>crit</i> | critical value, at critical point |
| <i>cs</i> | control surface |
| <i>cv</i> | control volume |
| <i>cyl</i> | cylinder |
| <i>eff</i> | effective |
| <i>EGR</i> | recycled gas |
| <i>eq</i> | equilibrium |
| <i>evap</i> | evaporation |
| <i>f</i> | fuel |
| <i>g</i> | gas |
| <i>i</i> | variable index, imaginary part of imaginary number |
| <i>ign</i> | ignition |
| <i>imp</i> | impingement |
| <i>in</i> | incoming |
| <i>inj</i> | injection |

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

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