Modelling wall interactions of a high-pressure, hollow cone spray

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Dipl.-Phys. Monika Mühlbauer

aus Amberg

Berichterstatter:	Prof. Dr.-Ing. Dr.-Ing. habil. C. Tropea
Mitberichterstatter:	Prof. Dr.-Ing. habil. M. Sommerfeld
	Priv.-Doz. Dr.-Ing. habil. I. Roisman
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Monika Mühlbauer

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Abstract

Spray/wall interactions significantly influence air/fuel mixing and emissions in modern spark-ignited, direct injection engines. Yet, the complex phenomena are hardly understood - especially not with respect to the large number of parameters and the associated wide ranges occuring in an engine. Modelling spray/wall interactions thus presents a major drawback in numerical simulations done in engine development.

This thesis focuses on the impact of dense, high-pressure hollow cone sprays for which existing wall interaction models are evaluated in detail and shown to fail. To the best of the author's knowledge no model adapted to the considered spray type was available which was furthermore accompanied by a severe lack of quantitative experimental data. Therefore, Phase Doppler Anemometry (PDA) is used to gather data on the normal impact of an isooctane spray with 50 bar injection pressure on a hemispherical copper target. The latter can be heated and wall temperatures up to 200°C are studied. Moreover, an additional oil film can be applied on the surface to simulate the oil film on a cylinder liner lubricating the piston motion. Variations in the particle Reynolds number between 2000 and 3000 on impact are achieved in changing the distance between injector and target.

As the question how PDA data concerning spray/wall interaction have to be evaluated has not been studied thoroughly yet, a fundamental analysis was carried out and is presented in this thesis. The results are not limited to dense and high-pressure, hollow cone sprays but may serve as general guidelines for future data evaluation.

Based on the measurements, the impact mechanisms of dense, high-pressure sprays are discussed where film fluctuations leading to ligament breakup are found to be decisive. For the considered high Reynolds numbers, inertial forces dominate all other forces which results in negligible parameter influence of the mean Reynolds number and the wall temperature. The oil film is observed to be quickly removed by the impacting spray which points out that spray/wall interactions on a cylinder liner may seriously endanger the operability of an engine.

Finally, empirical correlations describing the secondary spray on wall interaction are developed from the gathered data and an extrapolation to oblique impact is proposed. This first empirical model adapted to dense, high-pressure hollow cone sprays is implemented in numerical code in a Lagrangian approach. Details of the implementation are given. The model is validated in several cases for impact angles between 30° and 90° measured relative to the wall and for injection pressures of 50 bar and 200 bar with very good results.

Kurzzusammenfassung

Gemischbildung und Emissionen moderner direkt einspritzender Ottomotoren werden entscheidend durch Spray/Wand-Wechselwirkungen beeinflusst. Die damit verbundenen, komplexen Phänomene sind bisher jedoch kaum verstanden - insbesondere nicht im Hinblick auf die beträchtliche Anzahl an Parametern, die mit jeweils großem Wertebereich im Motorbetrieb vorkommen. Die Modellierung von Spray/Wand-Wechselwirkungen stellt deshalb einen Schwachpunkt in der zu einem Großteil mittels numerischer Simulationen durchgeführten Motorenentwicklung dar.

Die vorliegende Arbeit konzentriert sich auf den Aufprall dichter Hohlkegelsprays für den die Unzulänglichkeit existierender Modelle detailliert aufgezeigt wird. Nach bestem Wissen der Autorin gab es bisher kein für diesen Spraytyp geeignetes Wandwechselwirkungs-Modell, was zudem mit einem völligen Mangel an quantitativen experimentellen Daten verbunden ist.

Deshalb werden zunächst mittels Phasen Doppler Anemometrie (PDA) Daten zum normalen Aufprall eines Isooktansprays mit 50 bar Einspritzdruck auf ein halbkugelförmiges Kupfertarget gewonnen. Letzteres ist beheizbar, wobei Wandtemperaturen bis 200°C betrachtet werden. Zudem kann ein Ölfilm auf die Oberfläche aufgebracht werden, um den für die Kolbenbewegung entscheidenden Schmierfilm auf einer Zylinderbuchse nachzustellen. Durch unterschiedliche Abstände zwischen Target und Injektor wird beim Aufprall eine Variation der Reynoldszahl im Bereich von 2000 bis 3000 erreicht.

Da die Fragestellung, wie PDA Daten bezüglich Spray/Wand-Wechselwirkungen auszuwerten sind, bisher nicht ausreichend untersucht wurde, werden fundamentale Aspekte zur Datenauswertung analysiert und in der Arbeit dargestellt. Die Ergebnisse sind dabei nicht auf dichte Hohlkegelsprays beschränkt, sondern können als allgemeine Anleitung für zukünftige Datenauswertungen dienen.

Im Rahmen der Messauswertung wird der Aufprallmechanismus bei dichten Hohlkegelsprays diskutiert, wobei Filmfluktuationen, die zum Aufbruch von Ligamenten führen, identifiziert werden. Bei den betrachteten hohen Reynoldszahlen dominieren Trägheitskräfte alle anderen Kräfte, was zu einem vernachlässigbaren Parametereinfluss der Reynoldszahl und der Wandtemperatur führt. Ein Ölfilm wird durch das aufprallende Spray sehr schnell verdrängt. Dies verdeutlicht, wie Spray/Wand-Wechselwirkungen auf der Zylinderbuchse die Funktionsfähigkeit des Motors gefährden können.

Schließlich werden auf Basis der experimentellen Daten empirische Korrelationen zur Beschreibung des Sekundärsprays aufgestellt und eine einfache Extrapolation auf schiefe Aufprälle vorgeschlagen. Details der Implementierung dieses ersten empirischen Modells zur Wandwechselwirkung dichter Hohlkegelsprays in einem Lagrange-Ansatz werden erläutert. Anhand mehrerer Fälle wird das Modell für einen Aufprallwinkelbereich von etwa 30°-90° relativ zur Wand und für Einspritzdrücke von 50 bar und 200 bar mit sehr guten Ergebnissen validiert.

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Contents

List of Symbols

Abbreviations

cdf	cumulative distribution function	
pdf	probability density function	
BMW	Bayerische MotorenWerke	
CFD	Computational Fluid Dynamics	
COSY	COordinate SYstem	
DDM	Discrete Droplet Model	
DI	Direct Injection	
DNS	Direct Numerical Simulation	
LES	Large-Eddy Simulation	
PDA	Phase Doppler Anemometry	
RANS	Reynolds-Averaged Navier-Stokes equations	
RMS	Root Mean Square	
rpm	revolutions per minute	1/min
SEM	Scanning Electron Microscope	
SMD	Sauter Mean Diameter, D_{32}	m
SST	Shear-Stress-Transport turbulence model	

Dimensionless characteristic numbers

Ca	Capillary number, $\mathrm{Ca} = \frac{\mu_p \cdot v_p}{\sigma}$
CFL	Courant-Friedrichs-Lewy number
La	Laplace number, $\mathrm{La} = \frac{\rho_p \cdot \sigma \cdot D_p}{\mu_p^2}$
Nu	Nusselt number, $\mathrm{Nu} = \frac{h_c \cdot D_p}{\lambda_f}$

Oh	Ohnesorge number, $\mathrm{Oh} = \frac{\mu_p}{\sqrt{\rho_p \cdot \sigma \cdot D_p}}$	
Pr	Prandtl number, $\mathrm{Pr} = \frac{\mu_p \cdot c_P}{\lambda_p}$	
Re	Reynolds number, $\mathrm{Re} = \frac{\rho_p \cdot v_p \cdot D_p}{\mu_p}$	
Re*	another definition of the Reynolds number, $\mathrm{Re}^* = \frac{\rho_f \cdot v_s \cdot D_p}{\mu_f}$	
Sc	Schmidt number, $\mathrm{Sc} = \frac{\mu_p}{\rho_p \cdot \mathcal{D}}$	
Sh	Sherwood number, $\mathrm{Sh} = \frac{\beta_c \cdot D_p}{\mathcal{D}}$	
We	Weber number, $\mathrm{We} = \frac{\rho_p \cdot v_p^2 \cdot D_p}{\sigma}$	

Greek symbols

α, β	impact and reflection angle (between primary/secondary velocity vector and surface)	rad
α_ω, $\beta_{k/\omega}$, $\sigma_{k/\omega}$	constants in the k-ω model	-
α_p	angle between the particle velocity vector and the normal to the mean direction of both laser beams	rad
α_T	thermal expansion coefficient	1/K
$\bar{\Phi}$, Φ'	ensemble or time average and turbulent fluctuation of a scalar quantity Φ	
β_c	mass transfer coefficient	m/s
$\Delta\phi_{1-2}$	phase difference measured by two PDA detectors	rad
$\Delta\Theta$, $\delta\Theta$	width of Θ-classes oriented on target apex and on the mean impact area respectively	deg
$\Delta\Theta_{\mathrm{con},i}$	uncertainty of $\Theta_{\mathrm{con},i}$	deg
$\Delta\Theta_{\mathrm{prim}}$	angle range of the main impact area	deg
$\Delta\tilde{\Phi}_{\mathrm{vel}}$	spray diversification angle, used for primary data filtering	deg
δt	timestep of the Lagrangian phase	s
Δt_i	injection duration	s
Δt_{si}	time between two injections (from start to start)	s
δ	non-dimensional wall film thickness, $\delta = h_{\mathrm{film}}/D_{\mathrm{prim}}$	-
δ_{ij}	Kronecker symbol	-
ϵ_S, $\epsilon_{S,\mathrm{val}}$	relative signal presence of all detected and all validated signals respectively	-

$\epsilon_{\text{compression}}$	compression ratio	-
ϵ_{rel}	relative error of the mean of a scalar quantity X, $\epsilon = \sigma_{X_{10}}/X_{10}$	-
$\epsilon_{A,p}$, $\epsilon_{E,p}$	absorptivity and emissivity of a particle	-
$\eta_{\text{val},i}$	correction factor of drop i accounting for multiple and non-validated drops in the detection volume	-
$\Gamma^*_{X,k,\text{class}\,n}$	flux density (summed over all directions) of a scalar quantity X of the drops k in Θ-class n relative to that of all drops k	-
Γ_Φ	diffusion coefficient of a scalar quantity Φ	
γ_a, γ_z	non-dimensional, mean and peak-to-peak wall roughness, $\gamma_a = R_a/D_p$ and $\gamma_z = R_z/D_p$ respectively	-
$\Gamma_{X,k,\gamma}$	flux density of a scalar quantity X in direction $\vec{e}_\gamma$ of all drops k relative to that of all primary drops ($k = 1$)	-
$\Gamma_{X,k,\text{class}\,n}$	flux density (summed over all directions) of a scalar quantity X of the drops k in Θ-class n relative to that of all primary drops ($k = 1$)	-
$\Gamma_{X,k}$	flux density (summed over all directions) of a scalar quantity X of all drops k relative to that of all primary drops ($k = 1$)	-
κ	von Kármán constant	-
λ	thermal conductivity	W/(m·K)
Λ, τ, Υ	length, time and velocity scale of film fluctuations	m, s, m/s
λ_A	probability of drop appearance in the detection volume	-
λ_b, $\lambda_{\text{green/blue}}$	wavelength of a general or green/blue laser beam	m
λ_{air}	available air mass/air mass of a stoichiometric mass ratio	-
μ	dynamic viscosity	kg/(m·s)
μ_l	half axis ratio of the illuminated ellipsoid	-
μ_t	turbulent viscosity	kg/(m·s)
ν_{oil}	kinematic viscosity of oil	m^2/s
ω	tilt between COSYs for dry and wetted target surface	deg
ω	turbulent frequency	1/s
Φ	unspecified scalar quantitiy	
Φ_{op}	off-axis angle in a PDA setup (detection angle)	deg

Φ_{vel}	angle between velocity vector and wall	deg
Ψ	deviation angle (between impact and reflection plane)	rad, deg
Ψ_{op}	elevation angle in a PDA setup	deg
ρ	density	kg/m^3
σ	surface tension	N/m
σ, μ	fit parameters	-
σ_S	Stefan-Boltzmann constant	$\text{W/(m}^2\cdot\text{K}^4)$
σ_X	standard deviation of a quantity X	
$\sigma_{k/\varepsilon}$, $C_{\mu/\varepsilon1/\varepsilon2}$	constants in the k-ε model	-
$\sigma_{X_{10}}$	mean error of the mean X_{10}	
τ	non-dimensional time describing crown propagation	-
τ_e	time scale of a virtual eddy	s
τ_i	signal duration	s
τ_w	wall shear stress	N/m^2
τ_{ij}	component ij of the stress tensor	N/m^2
Θ	azimuthal angle on the hemispherical target	deg
Θ_0	azimuthal angle of the main impact area on the target	deg
Θ_1, Θ_2	smallest and largest value of Θ in $\Delta\Theta_{\text{con},i}$	deg
Θ_i	azimuthal angle of MP_i on the target	deg
$\Theta_{\text{class,min/max}}$	smallest and largest value of Θ in a considered Θ-class	deg
$\Theta_{\text{con,min/max}}$	minimal and maximal angle Θ where impacts can occur on the target	deg
$\Theta_{\text{con},i}$	azimuthal angle on the target where drop i impinges	deg
Θ_{op}	angle enclosed by two laser beams in a PDA setup	deg
$\tilde{\Phi}_{\text{vel,10}}$	mean angle between $U1$ and $V1$ for all drops impacting in the central Θ-class, equal to $\tilde{\Phi}_{\text{vel,10,central class}}$	deg
ε	turbulent dissipation rate	$\text{J/(kg}\cdot\text{s)}$

Latin symbols

Δh_{vap}	latent heat per mass unit	J/kg

$\dot{m}_{\text{inj}}$	injected mass flow rate	kg/s
$\dot{m}_{\text{stat}}$	injected mass flow rate for stationary needle lift	kg/s
$\dot{Q}$, $\dot{Q}_1$, $\dot{Q}_2$	volume flux of film fluid	m^3/s
$\dot{Q}_C$, $\dot{Q}_m$, $\dot{Q}_R$	convective heat transfer, transfer of latent heat and radiative heat transfer	J/s
$\dot{q}_i$	component i of a heat flux	$\text{J}/(\text{s}\cdot\text{m}^2)$
$\mathbf{A}$, $\vec{b}$	solution matrix and vector of a linearised problem	
$\mathcal{D}$	mass diffusity of the gaseous mixture	m^2/s
$\mathcal{R}$	fluid specific gas constant	J/(kg·K)
$\vec{e}$	unit vector	-
$\vec{e}_b$, $\vec{e}_1$, $\vec{e}_2$	unit vectors in beam direction	-
$\vec{e}_i$	unit vector parallel to the velocity vector of drop i	-
$\vec{e}_{pr}$	unit vector pointing from particle to receiver	-
$\vec{q}_X$	flux density vector of a scalar quantity X	
A	area	m^2
A, B, C	material-dependent constants in the Antoine equation	-
a, b, k	fit parameters	-
a, b, n, r, s	integers	-
a_0, b_0, c_0	lengths of the half axes of the illuminated ellipsoid	m
A_{impact}	impact area	m^2
A_{inj}	injection area	m^2
$A_{\text{val},i}$	validation area of drop i	m^2
$A_{\text{wall cell}}$	characteristic size of a wall cell	m^2
AT	arrival time of a particle in the measurement volume	s
AT_{rel}	relative arrival time of a particle in the measurement volume counted from the arrival of the first particle of an injection	s
C	constant in the logarithmic wall law depending on surface roughness	-
c	speed of light in the respective medium	m/s
C_D	drag coefficient	-
c_P	specific heat capacity at constant pressure	J/(kg·K)

C_S, R_S	terms in the definition of a general particle source term	
c_N	wall-normal restitution coefficient, $c_\mathrm{N} = v_{\mathrm{N,sec}}/v_{\mathrm{N,prim}}$	-
c_T	wall-tangential restitution coefficient, $c_\mathrm{T} = v_{\mathrm{T,sec}}/v_{\mathrm{T,prim}}$	-
D	drop diameter	m
d, d'	average blob diameter along a ligament and subblob size	m
d_i	distance between MP_i and target surface	m
$d_{\mathrm{inj.point}}$	distance between virtual injection point and target	m
$D_{B,0}$, $D_{B,1/2}$	average and arbitrary diameters resulting from a ligament	m
D_L, $D_{L,0}$	diameter of a ligament and its initial value	m
$d_{t,i}$, $d_{w,i}$	diameter of the detection volume for drop i and its projection onto the surface	m
DT	timestep of the Eulerian phase	s
e	internal energy per mass unit	J/kg
F	function dividing the secondary mass between child parcels	-
f_1, f_2, f_D	detected frequencies and difference frequency	Hz
f_b	frequency of a laser beam	Hz
f_{dev}	± 1, describes forward/backward scattering	-
f_{shift}	frequency shift in a Bragg cell	Hz
$F_{B,i}$	component i of the basset-history force	N
$F_{D,i}$	component i of the viscous drag force	N
$F_{EXT,i}$	component i of external forces	N
$F_{M,i}$	component i of the Magnus force	N
$f_{N/T,\mathrm{backward}}$	function relating the average normal/tangential momentum of secondary drops in backward direction to the average absolute primary momentum	-
$f_{N/T,\mathrm{forward}}$	function relating the average normal/tangential momentum of secondary drops in forward direction to the average absolute primary momentum	-
$F_{P,i}$	component i of the pressure gradient force	N
$F_{S,i}$	component i of the Saffman force	N
$f_{V,i}$	component i of a volume force	$\mathrm{N/m^3}$
$F_{VM,i}$	component i of the virtual mass force	N

fd_{calc}	coefficient describing $h_{\text{film}} \cdot (\sin\Theta)^{2/3}$, calculated for a given volume flux and determined from image evaluation respectively	m
G_k	production term of turbulent kinetic energy in the k-ε and k-ω model	J/(m^3·s)
h	enthalpy per mass unit	J/kg
h_c	heat transfer coefficient	W/(m^2·K)
h_l	thickness of the viscous boundary layer	m
h_{film}	wall film thickness	m
i, j, k	integers	-
I_d	minimal detectable intensity	m
$j_{n,i}$	component i of a diffusive flux of species n	kg/(m^2·s)
k	integer separating primary/secondary drops (primary drops $k = 1$, secondary drops assigned to the outside/ inside of the hollow cone $k = 2/3$),	-
k	turbulent kinetic energy per mass unit	J/kg
k_T	parameter used to define $f_{T,\text{forward}}$	-
L, L_0	target length at arbitrary and reference temperature	m
l_e	length scale of a virtual eddy	m
L_i, $\bar{L}_k$	Doppler burst length of drop i and mean of size class k	m
l_s	effective slit length	m
m	mass	kg
m_{inj}	injected mass	kg
N	number, e.g. the number of secondary child parcels per impact or the sample number	-
n	particle number rate (scaled with DT in CFX)	- (1/s)
N_P	number of parcels	-
n_{refr}	refractive index	-
$N_{\text{size classes}}$	number of size classes	-
N_D	number of drops passing through the detection volume	-
N_S, $N_{S,\text{val}}$	number of detected and validated signals respectively	-
p	pressure	Pa

p_{ambient}	ambient pressure	Pa
p_{inj}	injection pressure	Pa
p_{rand}	random number	-
p_{ref}	reference pressure	Pa
p_{vap}	vapour pressure	Pa
$q_{\text{E}_{\text{kin}},\gamma}$	kinetic energy flux density in direction $\vec{e}_\gamma$	$\text{J}/(\text{m}^2{\cdot}\text{s})$
$q_{\text{E}_{\text{tot}},\gamma}$	total mechanical energy flux density in direction $\vec{e}_\gamma$	$\text{J}/(\text{m}^2{\cdot}\text{s})$
$q_{\text{Nr},\gamma}$	number flux density in direction $\vec{e}_\gamma$	$1/(\text{m}^2{\cdot}\text{s})$
$q_{j\text{-mom},\gamma}$	j-momentum flux density in direction $\vec{e}_\gamma$	
$q_{m,\gamma}$	mass flux density in direction $\vec{e}_\gamma$	$\text{kg}/(\text{m}^2{\cdot}\text{s})$
$q_{V,\gamma}$	volume flux density in direction $\vec{e}_\gamma$	m/s
$q_{X,\gamma}$	flux density of a scalar quantity X in direction $\vec{e}_\gamma$	
$q_{X,k}$	flux density of a scalar quantity X for all drops k summed over all directions	
R_0	target radius	m
R_a, R_z	average and peak-to-peak surface roughness respectively	m
r_w	half the beam diameter at beam waist	m
R_{crown}	crown radius	m
S_Φ	source term of a scalar quantity Φ	
S_h	enthalpy source term	$\text{J}/(\text{m}^3{\cdot}\text{s})$
S_m	mass source term	$\text{kg}/(\text{m}^3{\cdot}\text{s})$
S_n	mass source term for species n	$\text{kg}/(\text{m}^3{\cdot}\text{s})$
S_p	particle source term	N/kg
$S_{p,i}$	component i of a momentum source term	N/kg
T	temperature	K
t	time	s
t^*	large time span compared to turbulent fluctuations	s
T_{ambient}	ambient temperature	K
t_{meas}	total measurement time	s
T_{sat}	saturation temperature	K

T_{wall}	wall temperature	K
$T_{L/N}$	Leidenfrost and Nukiyama temperature respectively	K
TT	transit time of a particle through the measurement volume	s
$U1$, $V1$	velocity components measured with PDA	m/s
$U1_{1-2}$, $V1_{1-2}$	measured phase difference for the respective detector pair	rad
$U2$, $V2$	velocity components after transformation	m/s
V	volume	m^3
v^+	non-dimensional velocity tangential to the wall given by the logarithmic wall law	-
v_i	component i of the velocity vector	m/s
V_L	volume of a ligament	m^3
v_s, $v_{s,i}$	vector amount and component i of the slip velocity between fluid and particle	m/s
v_τ	friction velocity	m/s
v_{inj}	injection velocity	m/s
$v_{\text{nozzle exit}}$	liquid velocity at nozzle exit	m/s
$w_{n,i}$	weight of drop i in Θ-class n	m
X	unspecified scalar quantity	
x, y, z	cartesian coordinates	m
x_i	component i of the coordinate vector	m
y^+	non-dimensional distance to the wall used in the logarithmic wall law	-
C_xH_y	unspecified hydrocarbon	
MP_i	measurement point i	

Subscripts

10	arithmetic mean
20	surface mean
30	volumetric mean
32	Sauter mean
a, b	after impact, before impact

B	blob
b	beam
f	fluid
L	ligament
p	particle
r	receiver
abs	absolute velocity
central	central Θ-class where most primary drops impact
central area	central Θ-class plus both neighbouring ones
class n	Θ-class n
deg	angle to be applied exceptionally in degrees
fit	denotes fitted quantities
flux	mean value calculated from flux density values
gev	generalised extreme value distribution
impro	characterises an improved mean value which includes correction and weighting factors
inj	injection
liquid	liquid
max, min	maximal, minimal value
meas	measured
N, T	normal and tangential to the considered surface
op	optics
prim	primary
sec	secondary
sec backward	secondary drops scattered in backward direction
sec forward	secondary drops scattered in forward direction
stat	stationary
total	total (secondary drops in all directions)
Weibull	Weibull distribution

Superscripts

$'$	characterises the turbulent fluctuation of a quantity	
$-$	characterises the ensemble or time average of a quantity	
$\rightarrow$	characterises a vector	

Extra symbols for Elsässer's model

α_r	virtual impact angle	rad
$\alpha_{\min}$	virtual profile angle	deg
β_r	virtual reflection angle	rad
$D_{\min}$	diameter limit	-
F_δ	polynomial in δ	-
$f_{n,\mathrm{sec}j,b}$	secondary to primary number rate ratio for child parcel j in boiling (HW)	-
$f_{n,brk}$	total secondary to primary number rate ratio for breakup (HNW)	-
$f_{n,sp}$	secondary to primary number rate ratio for splashing (CW/HW)	-
$h_{\mathrm{film,r}}$	wall film thickness in the virtual roughness profile	m
K	characteristic number, $K = \mathrm{We} \cdot \mathrm{Oh}^{-0.4}$	-
K_{dry}, K_S	parameters used to define the splashing criterion	-
s_{KD}	final splashing criterion	-
T^*_{CW}	non-dimensional wall temperature in CW	-
T^*_{HNW}	non-dimensional wall temperature in HNW	-
T^*_{HW}	non-dimensional wall temperature in HW	-
$T_{L/N,\mathrm{contact}}$	modified Leidenfrost and Nukiyama temperature respectively	K
$x_{\mathrm{D,sec}j,brk}$	secondary to primary diameter ratio for child parcel j for breakup (HNW)	-
$x_{\mathrm{D,sec}j,b}$	secondary to primary diameter ratio for child parcel j in boiling (HW)	-
$x_{\mathrm{m},b}$	secondary to primary mass ratio for boiling (HW)	-
$x_{\mathrm{m},sp}$	secondary to primary mass ratio for splashing (CW/HW)	-
$x_{c,sp}$	secondary to primary velocity ratio for splashing (CW/HW)	-

$x_{D,sp}$	secondary to primary diameter ratio for splashing (CW/HW)	-
CW	Cold wetting regime	
HNW	Hot non wetting regime	
HW	Hot wetting regime	
$\mathrm{We}_{\mathrm{crit}}$	critical Weber number separating different impact phenomena	-
$\mathrm{We}_{t,\mathrm{increase}}$	Weber number defined in HNW	-

Extra symbols for Kuhnke's model

α	impact angle relative to wall in deg	deg
α_r	impact angle relative to wall in rad	rad
$\bar{r}$	standard deviation from mean impingement point	m
η_{ha}	half axis ratio in the system of ellipses	-
κ	drop spacing	-
κ_j	spacing parameter in the elliptic ring j	-
λ_{MD}	blending factor between single and multiple drop correlations	-
ν_{32}	$D_{32,\mathrm{sec}}/D_{10,\mathrm{sec}}$	-
ν_{wf}	wall film mass in a computational cell scaled with impinging mass	-
ω	parameter used to define the deviation angle	-
A_j	area of elliptic ring j	m^2
B	function using a random number in the determination of the secondary to primary mass ratio	-
c_α	polynomial in α_r	-
c_{MD}	constant used in λ_{MD} for a wetted wall	-
D_L^*	non-dimensional, maximal spread of a lamella on drop impact	-
K	kinematic parameter, $K = \mathrm{We}_{\mathrm{N}}^{5/8} \cdot \mathrm{La}^{1/8}$	-
K_{crit}	critical value of K, separating splash	-
MD	multiple drop correlations	
r_j	length used to define the system of ellipses	m
SD	single drop correlations	

T^*	non-dimensional wall temperature	-
T^*_{crit}	critical, non-dimensional wall temperature separating adhesion and rebound for small values of K	-
t^*_{exp}	scaled expansion time of a drop lamella till maximal spread	-
t_{exp}	expansion time of a drop lamella till maximal spread	s

Extra symbols for Roisman's/Horvat's model

Γ_{Etot}	secondary to primary flux of total mechanical energy	-
Γ_V	secondary to primary volume flux and mass ratio	-
h_L	thickness of a lamella	m
K	kinematic parameter, $K = \text{We}_\text{N}^{0.8} \cdot \text{Re}_\text{N}^{0.4}$	-
K_{crit}	critical value of K separating splashing and deposition for not too small Weber numbers	-