Investigation of drop and spray impingement on a thin liquid layer accounting for the wall film topology

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In remembrance of Anna,
who kept me company
during the many nights
I spent on this thesis.

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbstständig verfasst und nur die angegebenen Hilfsmittel verwendet habe. Ich habe bisher noch keinen Promotionsversuch unternommen.

Darmstadt, den 26.10.2009 Nils Paul van Hinsberg

Preface

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Abstract

The single drop impingement processes upon steady and wavy liquid surface films of finite thickness and the spray impingement process onto rigid walls was studied both experimentally, as well as computationally and analytically. The global aim of the present study was to develop a mathematical model of the single drop and spray impingement process onto liquid wall films. To achieve this aim, the focus was put in particular on the description of the hydrodynamics of the wall surface film produced by spray impingement onto the wall, on a broader understanding of the physics involved in modeling of spray impingement processes and on the formulation of mathematical models based on experimental data and numerical simulations of the single drop impingement.

Two separate approaches were applied to obtain the necessary experimental and numerical results. The first approach focussed on the single drop impingement process upon steady and wavy liquid films of finite thickness, to understand in detail the physics behind the splash mechanism, the corona formation, the evolution of the cavity below the liquid surface and the typical time and length scales of the impingement process. For the impingement onto steady liquid films the influence of the thickness of the liquid wall film ($0.5 \leq h/D_d \leq 2.5$), the Weber number of the impinging drop ($130 \leq We \leq 600$) and the liquid properties (surface tension and viscosity) were studied, whereas besides these parameters also the phase of the wave at impingement ($0° \leq \varphi \leq 180°$) and the amplification of the wave (velocity and amplitude) were analysed for the impingement onto wavy liquid surface films. With the use of these parameters mathematical models of the impingement processes could be developed and implemented into the numerical codes for single drop and spray impingement.

The second approach was the direct measurement of the velocity distributions inside the wall film, produced by the impingement of an ultrasonic spray onto this rigid wall. The investigated variables on the velocity distributions were the impingement height of the spray, the volume flow of the spray within the range of $50\ \mathrm{mL/min} \leq \dot{V} \leq 400\ \mathrm{mL/min}$ and the use of the carrier gas. A new measurement technique was developed to obtain the distributions of the mean and fluctuating three-dimensional film velocities under bad light conditions. By measuring the wall film velocity distributions under realistic conditions, not only the unsteady wall film flow, generated by the surrounding drop impingements, was taken into account, but also the interactions of drops with other impinging drops, both in the spray and during the interaction with the wall film.

It was observed that for the single drop impingement onto steady wall films the penetration velocity of the cavity was constant and independent of all the investigated parameters, resulting in a direct relation between the time at which the cavity reached the bottom of the liquid film and the film thickness. A thicker film and/or a lower Weber number led to a lower radial expansion of the cavity, due to the larger surface tension forces acting on the cavity, resulting in a lower maximum diameter of the cavity. The time at which this maximum diameter was reached, was independent of the film thickness, but increased for higher Weber numbers. A faster receding and retraction of the cavity was observed for lower Weber numbers, but the time instant

of retraction was independent of the film thickness. The minimum residual film thickness was found to relate directly to the Reynolds number of the impinging drop ($h^*_{res} \sim Re^{-2/5}$), where it was observed that for very high Reynolds numbers the asymptotic value of the minimum residual film thickness increased for increasing thickness of the initial surface film. Concerning the numerical simulations, it was observed that the differences between the axi-symmetrical and the fully three-dimensional simulations were only minor; a clear difference, however, was found for the description of the receding phase of the cavity. For this part of the impingement process, the fully three-dimensional simulations led to a better correlation between the experimental data and the numerical simulations.

The study of the impingement of single drops onto solitary surface waves led to several important outcomes for spray impingement. It was found that the inclination and propagation of the surface film had a significant effect on the impingement outcomes, in particular on the time evolution of the shape of the cavity. The solitary surface wave introduced a relative velocity component upon impingement, which, together with the velocity distribution inside the liquid film, resulted in a clear increasing inclination of the cavity with time. Depending on the phase of the wave at impingement, a weak or strong interaction of one side of the expanding rim with the wave surface was observed, leading to an asymmetrical expansion of the cavity. The formation, strength and motion of the capillary waves changed magnificently for different phases of the wave, where the presence or absence of the capillary waves at the left and/or right side of the cavity, in combination with the unequal distribution of the surface tension forces over the cavity surface, induced an asymmetrical receding and retraction of the cavity, as well as an inclined Worthington jet. For higher Weber numbers a wider and deeper cavity was observed, together with a sharp increase of the inclination of the cavity. The values and the time instants of the maximum depth and diameter of the cavity were found to be independent of the phase of the wave; the former one, however, increased quadratically and the latter one linearly with higher Weber numbers. For large amplified waves, no correlation of the time and length scales with the Reynolds number was found.

To study the velocity distributions inside the liquid wall film at spray impingement, a new volumetric Particle Image Velocimetry technique was developed, based on micro-PIV and making use of a single digital camera, astigmatism and the spherical lens aberration. With this technique the tracer particle positions in depth could be encoded, after which the in-plane velocity fields at different layers, as well as the three-dimensional velocity fields in the investigated volume could be determined. With the use of this measurement technique it was found that the swirling motion of the spray was transferred directly to the liquid film in the form of large vortices inside the liquid film. The presence or absence of the carrier gas of the spray had a direct influence on the swirling direction and thus on the rotation direction of the vortices. An increase of the impingement height led to a decrease of the mean radial film velocities, as a result of the lower mean vertical velocities of the spray due to air resistance. An increase in the areas with relatively high mean radial film velocities, as well as an increase in the values of the maximum absolute film velocities, was found for larger volume flows. Strong film velocity fluctuations were found at the positions of saddle points and vortex cores.

Zusammenfassung

Der Aufprall von Einzeltropfen auf dünne Flüssigkeitsfilme mit ruhender und welliger Oberfläche und der Sprayaufprall auf feste Wände sind sowohl experimentell, als auch numerisch und analytisch untersucht worden. Das Hauptziel der vorliegenden Arbeit war die Entwicklung eines mathematischen Modells des Einzeltropfen- und Sprayaufpralls auf Flüssigkeitsfilme. Um dieses Ziel zu erreichen wurde der Schwerpunkt insbesondere auf die Beschreibung der Hydrodynamik von Oberflächenfilmen gelegt, die beim Sprayaufprall auf die Wand entstehen. Die Hauptthemen waren ein breiteres Verständnis der Physik, die in der Modellierung der Sprayaufprallprozesse involviert ist, und die Formulierung mathematischer Modelle, welche auf den experimentellen Daten und numerischen Simulationen des Einzeltropfenaufpralls basieren.

Zwei separate Vorgehensweisen wurden für die Erzeugung der benötigten experimentellen und numerischen Resultate verfolgt. Die erste Vorgehensweise konzentrierte sich auf den Aufprall von Einzeltropfen auf ruhige und wellige Flüssigkeitsfilme. Hiermit konnte ein detailliertes Verständnis der Physik des Splashmechanismus, der Entstehung der Krone, der Evolution des Kraters unter der Filmoberfläche und der typischen Zeit- und Längemaßstäbe des Aufprallprozesses erzielt werden. Für den Aufprall auf ruhende Flüssigkeitsfilme wurden der Einfluss der Wandfilmtiefe ($0.5 \leq h/D_d \leq 2.5$), die Weberzahl der aufprallenden Tropfen ($130 \leq We \leq 600$) und die Flüssigkeitseigenschaften (Oberflächenspannung und Viskosität) untersucht. Neben diesen Größen wurden für den Aufprall auf wellige Flüssigkeitsoberflächen auch die Phase der Welle beim Aufprall ($0° \leq \varphi \leq 180°$) und die Verstärkung der Welle (Geschwindigkeit und Amplitude) analysiert. Mit Hilfe dieser Größen konnten mathematische Modelle des Aufprallprozesses erstellt und in den numerischen Code für Einzeltropfen- und Sprayaufprall implementiert werden.

Die zweite Vorgehensweise basierte auf der direkten Messung der Geschwindigkeitsverteilungen in den Wandfilmen, welche sich beim Aufprall eines Ultraschallsprays auf eine feste Oberfläche einstellten. Die untersuchten Variablen, welche einen Einfluss auf die Geschwindigkeitsverteilung haben, waren die Aufprallhöhe des Sprays, der Volumenstrom des Sprays in einem Bereich von $50\ \mathrm{mL/min} \leq \dot{V} \leq 400\ \mathrm{mL/min}$ und die Verwendung des Trägergases. Eine neue Messtechnik wurde entwickelt, um die Verteilung der mittleren Filmgeschwindigkeiten und die Geschwindigkeitsschwankungen unter schwierigen Beleuchtungskonditionen zu bestimmen. Durch die Messung der Geschwindigkeitsverteilung im Wandfilm unter realen Bedingungen wurden zwei wichtige Parameter berücksichtigt. Dies ist zum einen die instationäre Wandfilmströmung, die durch den Tropfenaufprall in der Umgebung des Messpunktes resultiert, zum anderen die Interaktionen der Tropfen mit anderen aufprallenden Tropfen, sowohl im Spray als auch während der Interaktion mit dem Wandfilm.

Es wurde festgestellt, dass beim Einzeltropfenaufprall auf ruhende Wandfilme die Eindringgeschwindigkeit des Kraters konstant und unabhängig von allen untersuchten Parametern war. Dieses resultierte in einem direkten Zusammenhang zwischen dem Zeitpunkt, an dem der Krater den Boden des Flüssigkeitsfilms erreichte und der Tiefe des Films. Ein tieferer Film und/oder eine niedrigere Weberzahl entsprach aufgrund des größeren Einflusses der Ober-

flächenspannung auf den Krater einer niedrigeren Ausbreitung des Kraters und deswegen einem niedrigeren Wert des maximalen Kraterdurchmessers. Der Zeitpunkt, an welchem der maximale Kraterdurchmesser erreicht wurde, war unabhängig von der Filmtiefe, aber vergrößerte sich bei höhere Weberzahlen. Eine niedrigere Weberzahl resultierte in einem schnelleren Zurückgehen und Zurückziehen des Kraters; der Zeitpunkt des Zurückziehens des Kraters war jedoch unabhängig von der Filmtiefe. Es bestand ein direkter Zusammenhang zwischen der minimalen Filmtiefe und der Reynoldszahl des Aufpralltropfens, $h^*_{res} \sim Re^{-2/5}$. Hierbei wurde festgestellt, dass bei sehr hohen Reynoldszahlen der asymptotische Wert der minimalen residualen Filmtiefe sich bei größeren Tiefen des initialen Films erhöhte. In Bezug auf die numerischen Simulationen wurde festgestellt, dass die Unterschiede zwischen den rotationssymmetrischen und dreidimensionalen Simulationen geringfügig waren, lediglich bei der Zurückbildung des Kraters wurde eine deutliche Abweichung zwischen den beiden Simulationen beobachtet. Für diesen Teil des Aufprallprozesses zeigte die dreidimensionale Simulation eine bessere Korrelation mit den experimentellen Daten.

Die Untersuchung des Einzeltropfenaufpralls auf einzelne Oberflächenwellen lieferten einige wichtige Ergebnisse für den Sprayaufprall. So wurde gezeigt, dass die Neigung und Fortpflanzung des Oberflächenfilms eine erhebliche Auswirkung auf den Aufprallprozess hatten, insbesondere auf die zeitliche Entwicklung der Kraterform. Die einzelne Oberflächenwelle bringt eine relative Geschwindigkeitskomponente nach dem Aufprall ein, welche zusammen mit der Geschwindigkeitsverteilung im Film in eine zeitlich erhöhte Neigung des Kraters resultierte. Abhängig von der Phase der Welle beim Aufprall wurde eine schwache oder starke Interaktion einer Seite des sich ausbreitenden Kraters mit der Wellenoberfläche festgestellt, was eine asymmetrische Kraterausbreitung zur Folge hatte. Die Entstehung, Stärke und Bewegung der Kapillarwellen änderte sich deutlich mit der Änderung der Phase der Welle. Es wurde gezeigt, dass die An- oder Abwesenheit der Kapillarwellen an der linken und/oder rechten Seite des Kraters, in Kombination mit der ungleichmäßigen Verteilung der Oberflächenkräfte, sowohl ein asymmetrisches Zurückgehen und Zurückziehen des Kraters erzeugte, als auch einen geneigten Worthingtonjet. Eine höhere Weberzahl hatte einen breiteren und tieferen Krater und eine stark erhöhte Neigung des Kraters zur Folge. Die Werte und die Zeitpunkte des maximalen Durchmessers und der maximalen Tiefe des Kraters waren unabhängig von der Phase der Welle; die Erstgenannten stiegen quadratisch für höhere Weberzahlen an, die Zweitgenannten linear. Für stärkere Wellen wurde keine Korrelation zwischen den Zeit- und Längemaßstäben auf einer Seite und den Reynoldszahlen auf der anderen Seite gefunden.

Für die Untersuchung der Geschwindigkeitsverteilungen in dem Oberflächenfilm beim Sprayaufprall wurde eine neue, auf Mikro-Partikel-Image-Velocimetry basierte, volumetrische PIV-Technik entwickelt. Mit Hilfe dieser Technik konnte die Position der Tracerpartikel kodiert werden, woraus sich danach die Geschwindigkeitsfelder auf verschiedenen Ebenen, als auch die dreidimensionalen Geschwindigkeitsfelder berechnen ließen. Unter Anwendung dieser Messtechnik wurde festgestellt, dass die rotierende Bewegung des Sprays direkt an den Flüssigkeitsfilm übertragen wurde in Form von großen Wirbeln im Oberflächenfilm. Die An- oder Abwesenheit von Druckluft in der Düse hatte einen direkten Einfluss auf die Rotationsrichtung des Sprays und dadurch auch auf die Rotationsrichtung der Obeflächenwirbeln. Ein Anstieg der Aufprallhöhe führte zu einer Abnahme der mittleren radialen Filmgeschwindigkeiten. Dies ist in den niedrigen mittleren vertikalen Geschwindigkeiten des Sprays aufgrund des Luftwiderstandes begründet. Sowohl ein Anstieg der Flächen mit relativ hohen mittleren radialen Filmgeschwindigkeiten, als auch eine Erhöhung der maximalen absoluten Filmgeschwindigkeiten, wurde für höhere Volumenströme festgestellt. Starke Schwankungen in den Filmgeschwindigkeiten wurden an den Positionen der Sattelpunkte und der Wirbelzentren gefunden.

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Nomenclature

Symbol	Description	Unit
Alphabets		
A	Wave amplitude	m
a	acceleration	m/s^2
c	Velocity of sound	m/s
D	Diameter	m
d	Depth	m
D_{32}	Sauter Mean Diameter	m
f_d	Weighting factor	$-$
f	Focal length	m
	Frequency	$1/s$
g	Gravity acceleration	m/s^2
h	Surface film thickness	m
I	Overall intensity distribution	$-$
K	Critical splash threshold	$-$
k	Wave number	$1/m$
k_σ	Body forces	$kg/(m^2 \cdot s^2)$
$\mathscr{L}$	Local discretisation operator	$-$
L	Length scale	m
M	Magnification	$-$
$\mathbf{n}$	Normal vector	$-$
n	Index of refraction	$-$
P	Local intensity distribution	$-$
p	Pressure	$kg/(m \cdot s^2)$
p_g	Pressure drop associated with gravity	$kg/(m \cdot s^2)$
p_σ	Pressure drop associated with surface tension	$kg/(m \cdot s^2)$
Q	Source term	kg/s
q	Source term	kg/s
R_a	Surface roughness	m
R_2	Surface curvature	m
R	Correlation peak	$-$
	Radius	m
r	Radial component of spherical position vector	m
$\mathbf{S}$	Strain tensor	$1/s$
s	Particle movement	m

S	Splash criterion	$-$
	Surface	m^2
$\mathbf{T}$	Viscous stress tensor	$kg/(m \cdot s^2)$
T	Temperature	K
	Time	s
t	Thickness	m
	Time	s
TI	Turbulence intensity	$\%$
$\mathbf{U}$	Velocity vector	m/s
U	Velocity	m/s
u	x-component of velocity vector	m/s
U_{kin}	Kinetic energy	$(kg \cdot m^2)/s^2$
V	Volume	m^3
v	y-component of velocity vector	m/s
w	z-component of velocity vector	m/s
$\mathbf{x}$	Position vector	m
x	x-component of cartesian position vector	m
x_c	x-component of center of mass	m
y	y-component of cartesian position vector	m
y_{film}	Amplitude of oscillating film	m
y_c	y-component of center of mass	m
y_{cav}	Penetration depth of cavity	m
z	z-component of cartesian position vector	m
Z_0	Distance lens to imaging plane	m
z_0	Distance focal plane to lens	m

Greek symbols

α	Angle	$^\circ$
δ	Surface film thickness	m
Δ_s	Astigmatic difference	m
Δt	Time delay	s
	Time step	s
Δx	Initial distance between drop and liquid surface before impingement	m
Δz	Light-sheet thickness	m
Δz_0	Depth of measurement volume	m
δ_s	Fringe distance	m
δz	Depth of focus	m
ϵ	Light ray angle	$^\circ$
θ	Beam intersecting angle	$^\circ$
θ	Cone half angle	$^\circ$
θ	Inclined component of spherical position vector	$^\circ$
γ	Phase fraction	$-$
κ	Surface curvature	$-$
	Weighting factor	$-$
λ	Wave length	m
μ	Dynamic viscosity	$kg/(m \cdot s)$

	central moments ratio of the intensity distribution	m
μ_2	second order central moments of the intensity distribution	m^2
μ_4	fourth order central moments of the intensity distribution	m^4
$\overline{\mu}$	Mean value	$-$
ν	Kinematic viscosity	m^2/s
ρ	Aperture diameter	m
	Density	kg/m^3
σ	Surface tension	kg/s^2
	Value of standard deviation	$-$
τ	Time	s
τ_s	Relaxation time	s
τ_{rr}	Radial component of stress tensor	$kg/(m \cdot s^2)$
Φ	Phase shift	$^\circ$
φ	Wave phase	$^\circ$
	Azimuthal component of spherical position vector	$^\circ$
ψ	Detector angle	$^\circ$
	Flux limiter	$-$
Ω	Rotational velocity	$^\circ/s$
ω	Angular frequency	$1/s$

Superscripts

$(\ )^*$	non-dimensional variable
$\overline{(\ )}$	mean value
$(\ )'$	fluctuating part
$(\ )^0$	center value

Subscripts

$(\ )_0$	center, initial
$(\ )_a$	aperture, roughness
$(\ )_{ASOI}$	After Start Of Injection
$(\ )_{approx}$	approximated
$(\ )_b$	boundary layer
$(\ )_c$	curvature
$(\ )_{cav}$	cavity
$(\ )_{cr}$	critical
$(\ )_D$	Doppler
$(\ )_d$	drop
$(\ )_{diff}$	diffraction
$(\ )_f$	fluid phase
$(\ )_{film}$	liquid surface film
$(\ )_g$	gas phase
$(\ )_{imp}$	impingement

$(\ )_{max}$	maximum
$(\ )_{n}$	normal
$(\ )_{nd}$	roughness
$(\ )_{p}$	particle
$(\ )_{path}$	path
$(\ )_{r}$	radial direction
$(\ )_{r}$	relative
$(\ )_{\phi}$	azimuthal direction
$(\ )_{\theta}$	inclined direction
$(\ )_{res}$	residual
$(\ )_{sc}$	subcycles
$(\ )_{s}$	slip, surface
$(\ )_{T}$	splash
$(\ )_{tot}$	total, absolute
$(\ )_{trans}$	translational
$(\ )_{w}$	wall
$(\ )_{x}$	x-coordinate
$(\ )_{y}$	y-coordinate
$(\ )_{z}$	z-coordinate

Dimensionless numbers

Bo	Bond number, ratio of body forces to surface tension forces.
Ca	Capillary number, ratio of viscous forces to surface tension forces across interface liquid-gas.
Co	Courant number, conversion condition.
Fr	Froude number, ratio of kinetic energy to gravity forces.
La	Laplace number, ratio of surface tension forces to momentum transport.
Ma	Mach number, ratio of object velocity to velocity of sound.
Oh	Ohnesorge number, ratio of viscous to surface tension forces.
Re	Reynolds number, ratio of inertial to viscous forces.
We	Weber number, ratio of kinetic energy to surface tension forces.

Abbreviations

CCD	Charge Coupled Device
$DDPIV$	Defocusing Digital Particle Image Velocimetry
FOV	Field Of View
FVM	Finite Volume Method
HTA	Hot Wire Anemometry
LDA	Laser Doppler Anemometry

OpenFOAM	Open Field Operation and Manipulation
PDA	Phase-Doppler Anemometry
PISO	Pressure-Implicit with Splitting of Operators
PIV	Particle Image Velocimetry
PMMA	Polymethylmethacrylat
PTV	Particle Tracking Velocimetry
SMD	Sauter Mean Diameter
TOMO	Tomography
VOF	Volume-of-Fluid
WIDIM	Window Deformation and Iterative Multigrid

Chapter 1

Introduction

1.1 Overview

Splashing of drops on liquid layers and spray impingement occurs in many industrial applications involving multi-phase flow of liquid drops in a gas, such as inside internal combustion engines with direct fuel injection, where the fuel is sprayed into the engine cylinders in the form of small drops that splash on the inner sides of the engine walls, inside gas turbines, during spray drying, spray coating (including thermal plasma spraying, spray painting), spray cooling, etc. Investigations of the drop impingement onto liquid films have also importance in various agricultural and ecological fields, like the dispersion of anti-pesticides, the watering of the plants, thereby assuring an equal distribution of the water drops, and the dispersion of seeds and microorganisms. It is encountered frequently in nature, leading to various phenomena such as the electrification of waterfalls (Lenard [80]), thunderstorm electrification (Levin and Hobbs [83]) and the formation of air bubbles during heavy rains, and can also be found in medical applications (cooling of the skin during transplantation) and forensic investigations. Furthermore it is responsible for the corrosion of turbine blades.

Spray impingement on walls is either intentional and desirable, e.g. spray coating or cooling, or unavoidable, like for example for internal combustion engines. The impingement of the spray can intensify the spray heating and vaporization in a good way; on the other hand, however, the liquid film produced on the wall by the spray may produce negative effects such as enhanced soot formation and increased, unburnt hydrocarbons in internal combustion engines (Bai and Gosman [5], Griebel [51]).

Since the phenomena involved in the impingement of isolated drops onto various surfaces were the subject of many experimental, numerical and theoretical studies, of which a detailed overview can be found in the work of Rein [126], the single drop impingement can be modeled relatively well (Yarin and Weiss [196], Weiss and Yarin [185], Fukai *et al.* [46]). Spray impingement, involving multiple drop impingements, is much more complicated than the process of single drop impingement, because in spray impingement many interactions take place at the same time, i.e. impinging drops may interact with neighbouring drops, as well as two-sided interactions between impinging drops and the post-impingement products, like the corona and pinched-off secondary droplets. The experimental and numerical studies involving spray impingement have focussed mainly on the heat transfer between the heated surface and the impinging spray that forms a thin liquid film on this surface (Hall and Mudawar [54], Tilton *et al.* [166], Mudawar [101], Torres *et al.* [168]), as well as the identification of the different processes happening and products appearing during and after the spray wall interaction (secondary droplet diameters and velocities).

Most of the present models for spray impingement are based on the assumption that the results obtained for isolated drop impingements can be extrapolated to the case of a spray by using the superposition algorithm, where the same model for a single drop event is applied to each drop of the spray. This superposition principle is presumably valid for very sparse sprays, having a low drop density, but for most practical spray impingement applications this is not a very good approximation (Roisman *et al.* [133], Tropea and Roisman [171], Roisman and Tropea [134], Han *et al.* [55]).

Currently, several models are based on experiments performed with the successive and/or simultaneous impingement of two or more drops generated by monodispersed droplet streams, where the influence of multiple drop impingement onto dry surfaces or liquid surface films of known thickness on the interactions and impingement outcomes are investigated (Richter *et al.* [128], Bai and Gosman [4], Stanton and Rutland [161], Barnes *et al.* [8]).

Models of varying degrees of complexity are thus formulated on the basis of available data for the single drop impingement, in some cases with a complete neglect of the actual fluid mechanics or with a disregard for some influencing parameters. Most models incorporate a splash threshold condition, below which the impinging drop deposits completely and above which secondary droplets are formed after impingement. Many different forms can be found for this splash threshold, all validated by experimental data, but for different boundary conditions (smooth/rough surface, thin film/deep pool, below/above Leidenfrost temperature, etc.). In all of these models the interactions of impinging drops with neighbouring drops, as well as two-sided interactions between impinging drops and the post-impingement products, like the corona and pinched-off secondary droplets, are not taken into account. Furthermore, the influence of the waviness of the liquid surface film, induced by the simultaneous or subsequent impingements of neighbouring drops, on the spray impingement outcomes is being neglected. All of these phenomena result in complicated interactions of drops before impingement, with possible resulting satellite drops, as well as interactions of the coronas formed after impingement, which can lead to corona interactions and destructions and, depending on the inter-drop spacing and phase, in larger reatomised droplets. Because most models make use of the superposition principle these interactions are not taken into account, leading to increasing errors in the impingement description and modeling for poly-dispersed sprays at higher flux densities.

A possible solution to overcome the difficulties in modeling the interactions taking place during spray impingement is the direct numerical simulation of multiple drop impingement (Böhm *et al.* [15] and Böhm [14]). In this case, the multiple drop impingement can be simulated directly, leading to the interactions described above and the creation of an oscillating film. Polydisperse spray impingements, however, are characterized by different length and time scales, leading to several large drawbacks of this technique. The characteristic length scale of the film fluctuations may be much larger than the drop diameter and the characteristic time of such fluctuations is much larger than the typical time of drop impingement. This means that in order to describe the spray impingement numerically, a relatively large domain size is required with a very fine mesh. Second, the time step must be small enough to describe each drop impingement event. Moreover, a relatively large time duration must be simulated, such that a large number of drops have impinged, in order to represent the real statistics of the spray.

All this indicates that the accurate modeling of the spray impingement onto a liquid film is still far from optimum: the submodels presently used are based on too many assumptions, thereby neglecting several important physical properties of the spray impingement and introducing large errors. It can therefore be stated that the present experiments, based on single drop impingement studies onto steady deep pools, are not adequate for developing the necessary impingement submodels. It is therefore necessary to develop new submodels for spray impingement, which accurately represent the physics of spray impingement and take into account all the possible three-sided interactions between the impinging drops, the wavy liquid surface film and the post-impingement products. Additional experimental data are needed, in order to understand all the different parts of the spray impingement process, required to obtain and validate these new submodels for spray impingement.

First of all, the influence of the solid surface, at which the liquid surface film formed by the impinging spray is present, on the cavity evolution has to be investigated into more detail. The submodels, presently used for describing the evolution of the cavity shape in time, are mostly based on the experimental data of the single drop impingement onto deep pools. This means that the liquid film is much thicker than the diameter of the impinging drop, due to which no interaction between the cavity and the solid bottom of the liquid surface film takes place. Much research has been conducted in this area to understand the evolution of the maximum cavity depth in relation to the corona formation, splashing, the central jet height and bubble entrainment during impingement onto deep pools. For spray impingement, however, the thickness of the liquid surface film is of the same order as the diameter of the impinging spray drops. This results in clear interactions of the cavities, penetrating into the liquid film after impingement, and the solid bottom of the liquid film (Harlow and Shannon [56], Macklin and Hobbs [89], Shin and McMahon [153]). Not only do these interactions change the shape of the cavity, they also strongly influence the corona, resulting in a clear difference in shape, maximum diameter and maximum height for the corona, as well as the impingement products like the number and sizes of the secondary droplets and the shape and maximum height of the central jet. The physics behind these completely different outcomes for drop impingements onto liquid films of finite thickness need to be understood in detail, in order to change the present submodels in such a way to assure reliable and accurate predictions by the models in the near future.

Predicting the liquid film movement, like the waviness of the liquid film and the mean and fluctuating velocity distributions, is of particular importance in spray impingement applications. The waviness of the liquid film is an indication of how strong the thickness of the liquid film varies in time at a certain position or over a certain area. This is of great importance for spray cooling, where a continuous heat flux is required for a uniformly cooling of the complete surface of the object or keeping it at a constant temperature. A strong fluctuation in the thickness of the liquid film will result in a non-uniform cooling, which could result in a deformation of the surface during the cooling process. The velocity distributions inside the liquid surface film are also of great importance for spray cooling. The directions and magnitudes of these velocities give an indication in which direction and how fast the heat is being transported away from the hot surface, which parts of the hot surface are being cooled less and how fast the warm liquid is being refreshed by new cold liquid (Pautsch and Shedd [115], [116]).

In general, two methods exist for simulating the film dynamics. The first method applies the conservation laws for mass, momentum and energy, by making use of a control volume balance (Stanton and Rutland [161]), or integrates the conservation equations along the coordinate normal to the surface, after which a finite volume method is being used to solve these equations (Bai and Gosman [5]). The second approach uses a particle-based formulation, by tracking the film using Lagrangian numerical particles (O'Rourke and Amsden [109] and O'Rourke and Amsden [111]). In some of these studies, the authors assumed that the film inertia was negligible, but it was shown by Bai and Gosman [5] that this assumption is only valid under special conditions, meaning that the unsteady and convective terms should in general be included in the models for the liquid film.

The experimental verification of these submodels that describe the film dynamics at spray impingement, are very rare. Most of the experimentally conducted studies have focussed on the spray shape on the surface after impingement, as well as on the fraction of liquid mass deposited onto this surface (Ko and Arai [71], [72], Saito *et al.* [143], Weiss [186]). To model the spray impingement process onto a wavy liquid surface film of finite thickness, it is necessary to gather first of all knowledge about the influence of the surface waves on the impingement parameters, like the time evolution of the cavity, the behaviour of the corona and the central jet. It is clear that such an investigation cannot take place by looking at the impingement of a single drop during spray impingement, since in this case the influence of the surface waves on the impingement outcome cannot be isolated during a certain time period. Isolated drop impingements onto a surface wave, of which the physical parameters are known or can be obtained experimentally in an easy way, need to be conducted as a first step. The results of the inclined single drop impingement experiments onto steady liquid films show that the inclination of the liquid surface film relative to the drop velocity vector has a clear effect on the shape of the cavity after impingement (Zhbankova and Kolpakov [201], Leneweit *et al.* [81], Schotland [147], Jayaratne and Mason [65]). In comparison to these experiments, however, the liquid surface film for spray impingement is not steady and has a three-dimensional velocity, which is expected to have a strong effect on the impingement process, in particular on the time evolution of the cavity. It is therefore also of great importance to design a measurement technique, with which these three-dimensional film velocity distributions can be measured with a highly temporal and spatial resolution. The results may give an accurate indication of the order of magnitude of the mean and fluctuations of the film velocities in all three directions, which can be used to set correctly the boundary conditions for the liquid surface film in the numerical and theoretical models.

The extreme complexity of the spray impingement process makes it difficult to extract the desired information directly through experimental measurements. Moreover, it is difficult and time-consuming to isolate a certain parameter to investigate the influence of this selected parameter on the spray impingement outcomes, since all influencing key parameters (pressure, drop velocities, drop sizes, volume flow, liquid properties, film thickness, etc.) are linked together in some complex way. A change in surface tension of the liquid, for example, also changes indirectly the drop velocity and size distributions of the spray, as well as the waviness of the liquid surface film.

These considerations have provided the motivation for the present study, which is aimed at the development and assessment of the mathematical models of the physical processes involved in the impingement of sprays, in particular the evolution of the cavity in time for impingement onto steady and wavy liquid surface films of finite thickness and the three-dimensional structure of the velocity fields inside the surface film.

1.2 Objectives and contributions of the present study

The global aim of the present study is to develop a model of spray impingement onto a rigid wall. This study focusses in particular on the description of the hydrodynamics of the wall surface film produced by spray impingement onto the wall, a broader understanding of the physics involved in modeling of spray impingement processes and the formulation of mathematical models based on experimental data and numerical simulations.

First, an extensive and detailed literature study has been performed to gain insight into the basic physics of single drop and spray impingement onto liquid surface film of finite thickness, the flow of liquid surface films and the presently existing measurement techniques to obtain three-dimensional and three-component velocity fields. With the help of this knowledge, experiments have been conducted to observe the outcomes of single drop impingements onto steady liquid surface films and onto a solitary surface wave, focussing in particular on the time evolution of the shape of the cavity inside the liquid surface film and the interactions of the cavity with the rigid wall. The results of these experiments have been used to derive mathematical models of these processes and to implement these into a numerical code. Finally, the drop impingement simulations are assessed against the experimental data and the theoretical descriptions.

Concerning the spray impingement processes and in particular the hydrodynamics of the surface film, a new planar measurement technique has been designed and validated, with which the mean and fluctuating planar velocity components inside the liquid surface film have been obtained experimentally.

In this study the following specific contributions to spray/wall interaction modeling have been:

- Development of a general mathematical model for the time evolution of the depth of the cavity after impingement on the basis of the experimental findings. This model has been developed accounting for the liquid inertia, viscosity, gravity and surface tension. It is capable of predicting the penetration depth of the cavity during the initial time instants after impingement onto steady liquid surface films of finite thickness.

- Development of a mathematical model for the time evolution of the diameter of the cavity during the expansion and receding phases, based on the experimental findings and numerical simulations of the impingement onto steady liquid surface films of finite thickness. This model is based on the kinematic discontinuity approach. The mass and momentum balance equations of the liquid layer are applied to account for the inertial effects, surface tension and gravity. A remote asymptotic solution for the temporal evolution of the cavity diameter is derived, with which also the maximum diameter of the cavity and the time instant at which this maximum cavity diameter is reached, can be calculated. This model takes into account the contributions of the impinging drop, like the Weber number of the drop, the initial liquid surface film thickness and the liquid properties. With this model the typical length scales and time scales, important for spray impingement, are derived.

- Incorporation of an advanced free-surface capturing model for single drop impingement onto liquid films of finite thickness into a numerical code. The model is based on a two-fluid formulation of the classical volume-of-fluid model in the framework of the finite volume numerical method. A modified pressure term is introduced into the momentum equation, as well as an additional convective term into the transport equation for the phase fraction, contributing to a sharper interface resolution, thereby introducing a relative velocity between the gas phase and the liquid phase. This model is capable of predicting in a three-dimensional space the time evolution of the cavity shape, the diameter and the penetration depth for single drop impingements onto steady liquid surface films and solitary surface waves.

- Development of a general theoretical model to approximate the minimum residual thickness of the surface film below the cavity after drop impingement based on the numerical simulations. This model is capable of predicting the minimum thickness of the residual surface film for impingements onto films of variable thickness.
- Determination of the shape and velocity components of the capillary waves, which indirectly influence the minimum residual thickness of the surface film, by means of experiments and numerical simulations.
- Determination of the time evolution of the depth and diameter of the cavity for the expansion and receding phases after single drop impingement onto a solitary wave, by means of experiments and numerical simulations. A large data library is obtained for impingements onto solitary waves with small and large amplitudes, for different Weber numbers of the impinging drops and different properties of the liquids.
- Development of a new three-dimensional, three-component planar measurement technique based on micro-Particle Image Velocimetry in combination with two aberrations. With this measurement technique the three-dimensional velocity distributions at arbitrary depths inside the measurement volume can be obtained.
- Determination of the radial mean and fluctuating velocity distributions of the liquid surface film, produced by spray impingement, by means of the new three-dimensional, three-component planar measurement technique. A large data library is obtained for spray impingements onto a thin liquid surface film, for different Weber numbers of the impinging drops of the spray, volume flows, nozzles and spray geometries.

1.3 Thesis outline

In Chapter 2 a review of the previous investigations on theoretical, experimental and numerical studies of the single drop impingement characteristics, the multiple drop impingement, the dynamics of the liquid surface film formed by impinging sprays and the different multicomponent planar particle velocimetry measurement techniques is given. First, the most important components of single drop impingement on dry and wetted surfaces, the different impingement regimes and associated impingement criteria are reviewed. Second, an overview of the experimental, numerical and theoretical studies of the interaction and impingement of two successive drops and of the spray impingement onto solid and wetted surfaces is presented. This is followed by a survey of the aspects regarding liquid wall flows. Finally, a very broad overview of the different multi-component planar particle velocimetry measurement techniques, making use of planar light sheets or volume illumination, is given.

The discussion of the experimental arrangements and the obtained results has been split up into three main parts. The first part (Chapter 3 to Chapter 5) focusses on the single drop impingement process onto steady and wavy liquid films. The spray impingement process is discussed in the second part of this thesis (Chapter 6 and Chapter 7), whereas in the third part the newly developed volumetric particle image velocimetry technique is presented (Chapter 8).

Chapter 3 presents the different experimental arrangements designed to investigate the single drop impingement processes. Two different experimental arrangements are presented: for drop impingement studies onto a steady surface film and onto a solitary surface wave. This is followed by an overview of the values of the investigated parameters. This chapter finishes with a description of the shadowgraphy measurement technique that is used for the acquisition of the desired measurement data, together with the adaptation of the technique to the experimental arrangement and the associated data analysis and post-processing.

In Chapter 4 the results of the single drop impingement processes onto steady liquid films of finite thickness and are presented. The influences of the initial liquid film height, the terminal velocity of the drop before impingement and the properties of the liquids on the outcomes of the impingement process are first investigated by means of the observations made by the shadowgraph images. This is followed by a detailed analysis of the experimental, analytical and numerical results of the diameter and depth of the cavity, appearing below the liquid film upon single drop impingement onto a steady liquid surface film of finite thickness. A mathematical derivation of the model for the time evolution of the diameter of the cavity during the expansion and receding phases is presented. A remote asymptotic solution for the temporal evolution of the cavity diameter is derived, with which the value and the time instant of the maximum cavity diameter can be calculated. This model is compared with the experimental and numerical results for the change of the diameter of the cavity during the initial phase of the complete impingement process. This is followed by a detailed analysis of the results of the time evolution of the diameter and depth of the cavity for the complete impingement process. The differences in the cavity evolution for a change in the initial liquid surface film thickness, in Weber number of the impinging drop and in the liquid properties are described and analysed. The final part of this chapter focusses on the derivation of a scaling analysis of the minimum residual film thickness on the wall and the comparison of this model with the numerical simulations.

In Chapter 5 a detailed analysis of the results of the single drop impingement measurements onto a solitary surface wave, in particular the depth and diameter evolution of the cavity in time, is given. First, the observations of the single drop impingement processes onto solitary surface waves are presented. These results are compared with the observations of the impingement onto steady liquid films, in order to investigate the influence of the waviness, velocity and amplitude of the surface film upon impingement. For this comparison the terminal velocity of the drop before impingement, the phase of the wave at impingement, the amplitude and velocity of the wave and the properties of the liquids are changed. This is followed by the outcomes of the single drop impingements onto standing waves, where the inclination of the surface wave and velocity of the drop upon impingement play a central role. In the next part of this chapter the differences in the cavity evolution for a change in the inclination of the liquid surface upon impingement, hence the phases of the wave, in Weber number of the impinging drop, in the amplification of the solitary surface wave (velocity and amplitude) and in the liquid properties are described and analysed. Here the emphasis is put on the time evolution of the diameter and depth of the cavity appearing below the liquid upon drop impingement.

Chapter 6 presents the experimental arrangement designed to investigate the spray impingement process. The experimental arrangement is discussed, followed by an overview of the values of the investigated parameters. This chapter finishes with a description of the different measurement techniques that are used for the acquisition of the desired measurement data. These are the Phase-Doppler Anemometry technique and the Particle Image Velocimetry technique. For both techniques the adaptation to the experimental arrangements is explained, together with the associated data analysis and post-processing.

Chapter 7 is concerned with the results of the spray impingement measurements. The first part focusses on the characterisation of the spray by means of the Phase-Doppler Anemometry technique, resulting in the distribution of the drop diameters, drop mean vertical velocities, mass distribution and kinetic energy distribution of the impinging sprays. The second part discusses the results of the mean radial velocity distributions and velocity fluctuations inside the surface film for spray impingement.

In Chapter 8 the so-called volumetric Particle Image Velocimetry technique is presented. First of all a detailed overview of the different possible monochromatic and chromatic aberrations is given, followed by an explanation of the resulting optical imaging and the applied calibration method, as well as a discussion of the different steps of the image processing and post-processing. The final part of this chapter focusses on the validation of the measurement technique by using a thin laminar flow.

Finally, in Chapter 9, the main achievements of this thesis are summarised, and suggestions for future work are given.