Influence of Ice Formation on Drop Dynamics

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I dedicate this thesis to my parents and my life partner Julia for their exhaustless encouragement, support and patience during my doctoral candidature.

Hiermit versichere ich, die vorliegende Doktorarbeit unter der Betreuung von Prof. Dr.-Ing. C. Tropea und Apl. Prof. Dr.-Ing. S. Jakirlić nur mit den angegebenen Hilfsmitteln selbständig angefertigt zu haben.

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Abstract

Atmospheric icing occurs when supercooled large drops (SLD) of water come in contact with the surface of exposed structures. Excessive accumulation on structures and equipment is well known for causing serious problems in cold-climate regions which lead to material damage and high costs in various sectors of the economy. Airframe icing is a topic of great interest to aerospace industry; it is mainly concerned with the safe and efficient operation of an aircraft. Hereby, SLD impact violently with the skin of the aircraft and as consequence an ice layer grows which covers the surface of the airplane. The initial objective of this study consists in to gain a better understanding of the fluid mechanics of the impacting/shedding drop without phase change and the thermodynamics governing the crystallization process. Both, numerical and experimental investigations are conducted; experiments on drop shedding are carried out at the Department of Mechanical Engineering, Lassonde School of Engineering in Toronto. The modeling of the crystallization process represents the most challenging part of this work.

This study allows, inter alia, for modeling both stages of the solidification process of a SLD of water on a cold substrate - the first rapid, recalescent stage and the second slower, quasi-isothermal stage. The different mechanisms underlying both freezing stages can be explained as follows: in the first stage the initial planar solidification front becomes morphologically unstable due to a high degree of supercooling. Small bumps/instabilities evolving at the interface propagate further into the liquid. During this transition process the small bumps at the solid-liquid interface develop into crystals of different shapes. A small fraction of the drop freezes instantaneously, until the thermal energy rate originating from supercooling is exhausted. The crystallization can be modeled as growing front of needle-like dendrites. In the second stage, the cold substrate cools the water between the needles and, accordingly, the crystallization front grows up planar from the cold boundary. The velocity of the solidification front is considerably lower than the freezing velocity in the first stage. The second stage can be mathematically described as a stable one-dimensional solidification process.

Kurzfassung

Das Thema der Vereisung (engl. Icing) ist ein aktuelles Forschungsfeld, an dem ein direktes, öffentliches (gesellschaftliches und politisches) Interesse besteht. Dies liegt daran, dass Vereisung unmittelbar mit hohen Risiken und Kosten verknüpft ist. In der Vergangenheit gab es z.B. zahlreiche Flugzeugunfälle, die auf Vereisung von Tragflächen oder mechanischen Komponenten des Flugzeuges zurückzuführen sind. Die Eisanlagerung entsteht hauptsächlich beim Durchfliegen von niedrig liegenden Wolken mit unterkühlten Wassertropfen. Die Wassertropfen prallen auf die Flugzeugoberfläche auf und vereisen. Die gebildete Eisschicht kann die Flugzeugeigenschaften derart beeinträchtigen, dass es sogar, von erhöhten Transportkosten abgesehen, zu dramatischen Unfällen führen kann. Ziel dieser Arbeit ist ein tiefergehendes Verständnis für die hydro- und thermodynamischen Prozesse der vereisenden, unterkühlten Wassertropfen zu erlangen. Das Verhalten von aufprallenden (Impact) und fließenden (Drop Shedding) Wassertropfen ohne Phasenwechsel wird experimentell und mithilfe von CFD-Simulationen untersucht. Für die Shedding-Experimente hat man den Windkanal an der Lassonde School of Engineering in Toronto verwendet. Der in zwei Stufen ablaufende Gefrierprozess von unterkühlten Wassertropfen mit Wandinteraktion wird modelliert und anhand numerischer Ergebnisse validiert. In der ersten Stufe der Vereisung wird die anfänglich ebene Erstarrungsfront, bedingt durch heterogene Nukleation, aufgrund eines hohen Unterkühlungsgrades morphologisch destabilisiert. Kleine Unebenheiten entstehen an der Wasser-Eis-Grenzfläche. Diese Instabilitäten wachsen an der Grenzfläche zu kristallartigen Strukturen. Dabei gefriert nur ein kleiner Teil des Tropfens nach der ersten Vereisungstufe, unmittelbar bis die thermische Energie der anfänglichen Unterkühlung im Tropfen ausgeschöpft ist. Die Kristallisationsfront kann als eine Ansammlung von wachsenden, nadelähnlichen Dendriten modelliert werden. In der zweiten Stufe kühlt das kalte Substrat das verbliebene, flüssige Wasser im Tropfen. Das flüssige Wasser vereist stabil und eine zweite, planare Kristallisationsfront wächst von unten nach oben. Die zweite Stufe kann als eine stabile Erstarrungsfront modelliert werden.

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Nomenclature

Latin letters

Upper case

Symbol	SI base units	Description
A	m^2	cross-sectional area
A_{cell}	m^2	cross-sectional area of array cell
A_D	m^2	frontal area of the sessile drop
Ca	-	capillary number
C_D	-	drag coefficient
C_L	-	lift coefficient
D	m	drop diameter
D^0	m	initial drop diameter
D_z	m	spreading diameter
$\tilde{D}_z$	-	non-dimensional spreading diameter
F_{adh}	kg m/s^2	adhesion force
F_{drag}	kg m/s^2	drag force
H_D	m	height of the sessile drop
I	-	Ivantsov function
L	m^2/s^2	latent heat of crystallization
L_{eff}	m	effective diameter of the wind tunnel
L_v	kg/(s^2 m)	volumetric latent heat of crystallization
Ma	-	Mach number
Pe	-	Peclet number
R	m	radius of nucleus
R_c	m	critical radius
R_D	m	base area radius of the sessile drop

R_{eff}	m	effective radius
R_I	m	instability radius
Re	-	Reynolds number
Re^0	-	initial Reynolds number
Re_∞	-	cross-flow Reynolds number
Re_c	-	critical Reynolds number
S	m	perimeter of the cross-section
$\boldsymbol{S_f}$	-	unit surface normal vector
S_f	m^2	surface area
St	-	Stefan number
St^0	-	Stefan number at initial time step
T	K	temperature
T^0	K	temperature at initial time step
T_{bath}	K	temperature in the chilling system's bath
T_B	K	temperature at domain boundary
T_f	K	interface temperature
T_l	K	temperature of liquid phase
T_m	K	melting/crystallization temperature
T_s	K	temperature of solid phase
T_{sub}	K	substrate temperature
U	m/s	velocity
U^0	m/s	initial drop velocity
U_∞	m/s	cross-flow velocity
U_{air}	m/s	airflow velocity
U_{crit}	m/s	critical cross-flow velocity
U_{char}	m/s	characteristic cross-flow velocity
V	m/s	constant crystal's tip velocity
V_D	l	drop volume
X	m	thickness of the solid front
We	-	Weber number
We^0	-	initial Weber number
$We_{\infty,\text{c}}$	-	critical cross-flow Weber number

Lower case

Symbol	SI base units	Description
a	m	needle radius
$\tilde{a}$	-	non-dimensional needle radius
c_l	$m^2/(s^2\ K)$	specific heat capacity of liquid phase
c_s	$m^2/(s^2\ K)$	specific heat capacity of solid phase
c_v	$kg/(s^2\ m\ K)$	volumetric heat capacity
$c_{v,l}$	$kg/(s^2\ m\ K)$	volumetric heat capacity of liquid phase
$c_{v,s}$	$kg/(s^2\ m\ K)$	volumetric heat capacity of solid phase
d	m	drop diameter
$\boldsymbol{d}$	-	unit vector indicating flow direction
d_s	-	symmetry value
e	$kg\ m^2/s^2$	internal energy
erf	-	error function
erfc	-	complementary error function
f	-	friction factor
f_{Hoff}	-	Hoffman function
h_s	m	thickness of aluminum sheet
k	$kg\ m/(s^3\ K)$	heat conductivity
k_l	$kg\ m/(s^3\ K)$	heat conductivity of liquid phase
k_s	$kg\ m/(s^3\ K)$	heat conductivity of solid phase
k_{kin}	K s/m	kinetic coefficient
l_d	m	length of the initial needle
l_{dec}	m	decay length
m	kg	mass
$\boldsymbol{n}$	-	unit vector normal to solid-liquid interface
$\boldsymbol{n}_f$	-	normal unit vector on boundary face
$\boldsymbol{n}_s$	-	unit vector normal to substrate
p	$kg/(m\ s^2)$	pressure
p_0	$kg/(m\ s^2)$	ambient pressure
r_t	m	tip radius of dendrite
t	s	time

v_{cl}	m/s	propagation velocity of the contact line
v_n	m/s	normal interface velocity
v_n^0	m/s	characteristic velocity of the system
v_t	m/s	tip velocity of dendrite
v_{tot}	m/s	total velocity of the solid-liquid interface
$v_{t,\text{exp}}$	m/s	dendrite tip velocity from experiments
v_ρ	m/s	component of interface velocity due to density jump
$\boldsymbol{x}$	m	position vector

Greek letters

Upper case

Symbol	SI base units	Description
Γ	m K	capillary constant
Δ	-	dimensionless supercooling
ΔT	K	initial supercooling
ΔT_{kin}	K	kinetic undercooling
ΔT_t	K	total undercooling
ΔT_Γ	K	capillary undercooling
Θ	°/-	angle/non-dimensional temperature
Θ_a	°	advancing contact angle
Θ_d	°	dynamic contact angle
Θ_{down}	°	downstream contact angle
Θ_e	°	equilibrium contact angle
Θ_r	°	receding contact angle
Θ_s	°	static contact angle
Θ_{up}	°	upstream contact angle
Ξ	-	solid-liquid interface
Φ	m	level set distance function
Ω_l	-	liquid phase of the domain

Ω_s	-	solid phase of the domain

Lower case

Symbol	SI base units	Description
α_l	m^2/s	thermal diffusivity of liquid phase
α_s	m^2/s	thermal diffusivity of solid phase
β	-	volume of fluid indicator function
δ	m	amplitude of sinusoidal perturbation
δ_c	m	capillary length
δ_d	m	thermal diffusion
γ_a	-	anisotropic factor
ϵ	-	parameter in marginal stability theory
κ_{lg}	1/m	curvature of liquid-gas interface
κ_{sl}	1/m	curvature of solid-liquid interface
λ	-	root of transcendental equation
λ_c	m	cutoff wavelength
λ_f	m	wavelength of fastest growing mode
λ_s	m	spacing between dendrites
$\tilde{\lambda}_s$	-	non-dimensional spacing between dendrites
μ	-	interaction parameter
μ_g	kg/(s m)	dynamic viscosity of the gaseous phase
μ_l	kg/(s m)	dynamic viscosity of the liquid phase
ν_g	m^2/s	kinematic viscosity of the gaseous phase
ν_l	m^2/s	kinematic viscosity of the liquid phase
ξ	-	material coordinate
ρ	kg/m^3	density
ρ_g	kg/m^3	density of gaseous phase
ρ_l	kg/m^3	density of liquid phase
ρ_s	kg/m^3	density of solid phase
σ	kg/s^2	surface tension

σ_a	kg/s^2	anisotropic surface tension
σ_{lg}	kg/s^2	surface tension of liquid-gas interface
σ_{sl}	kg/s^2	interfacial tension of solid-liquid interface
τ_w	kg/(s^2 m)	wall shear stress
$\tilde{\tau}$	-	non-dimensional time
ϕ	m^3/s	flux
ϕ_{gf}	m^3/s	flux at ghost face

Abbreviations

Symbol	Description
AMP	amplitude
AT	ambient temperature
ave	average
BC	boundary condition
CA	contact angle
CAH	contact angle hysteresis
CDS	central differencing scheme
CSF	continuum surface force
CV	control volume
DI	deionized
DNS	direct numerical simulations
FPS	frames per second
IB	immersed boundary
IDGE	isothermal dendritic growth experiments
IWT	icing wind tunnel/interfacial wave theory
LS	level set
MAC	marker and cell
max	maximum
MB	moving boundary
min	minimum
MST	marginal stability theory
MT	microsolvability theory
MVH	maximum velocity hypothesis
OMB	oscillator model of branching
PDMS	polydimethylsiloxane
PF	phase field
PISO	pressure implicit with splitting of operators
PMMA	polymethylmethacrylate
PTFE	polytetrafluoroethylene

SCN	succinonitrile
SEIL	surface engineering and instrumentation laboratory
SHS	superhydrophobic surface
SIMPLE	semi-implicit method for pressure linked equations
SLD	supercooled large droplet
TS	test section
ULDG	universal law of dendritic growth
VOF	volume of fluid
2D	two-dimensional
3D	three-dimensional

Contents