Impact characteristics of liquid nitrogen droplets

Michiel AJ van Limbeek,

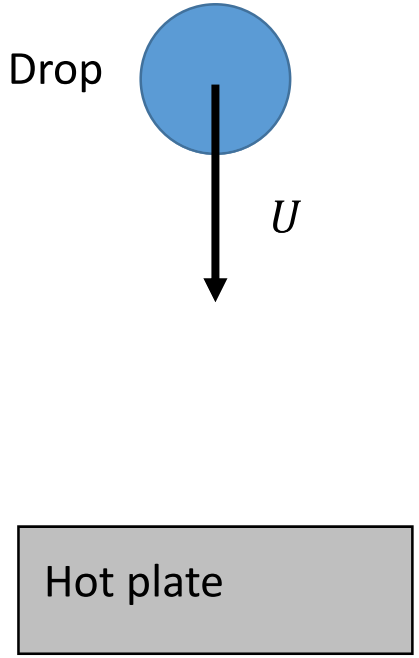
Thomas Nes, Marcel ter Brake and Srinivas Vanapalli

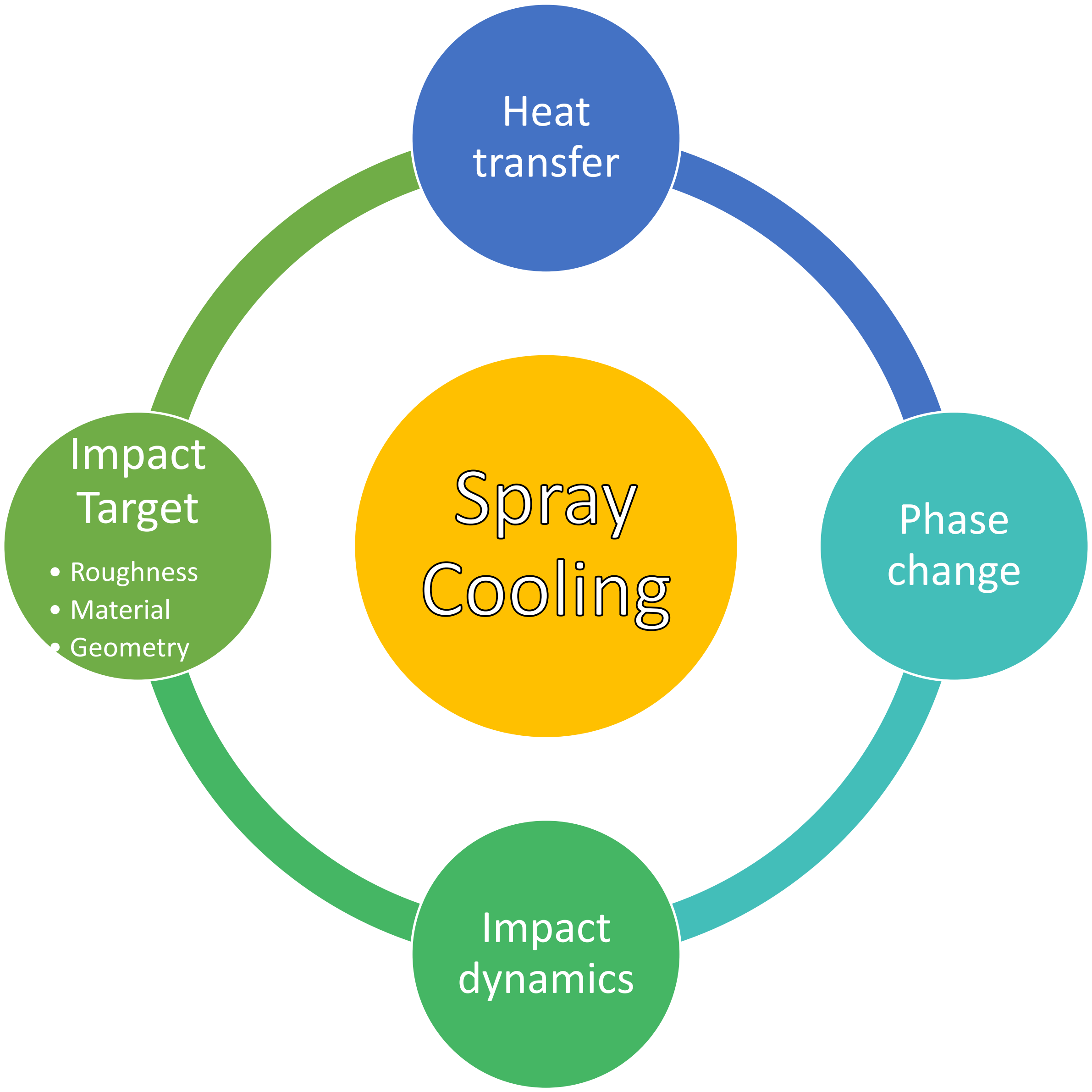
UNIVERSITY OF TWENTE.

Physics of Fluids

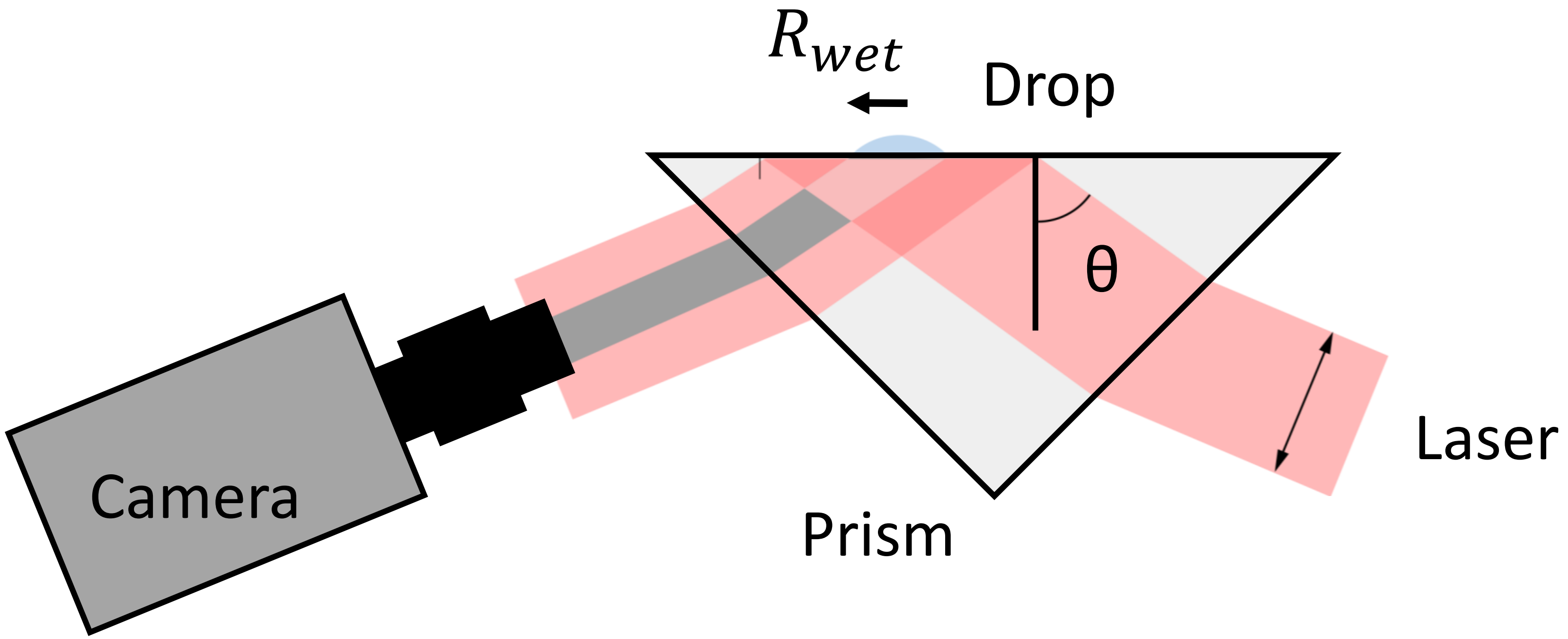
Spray cooling

$$\dot{Q}\ ?$$



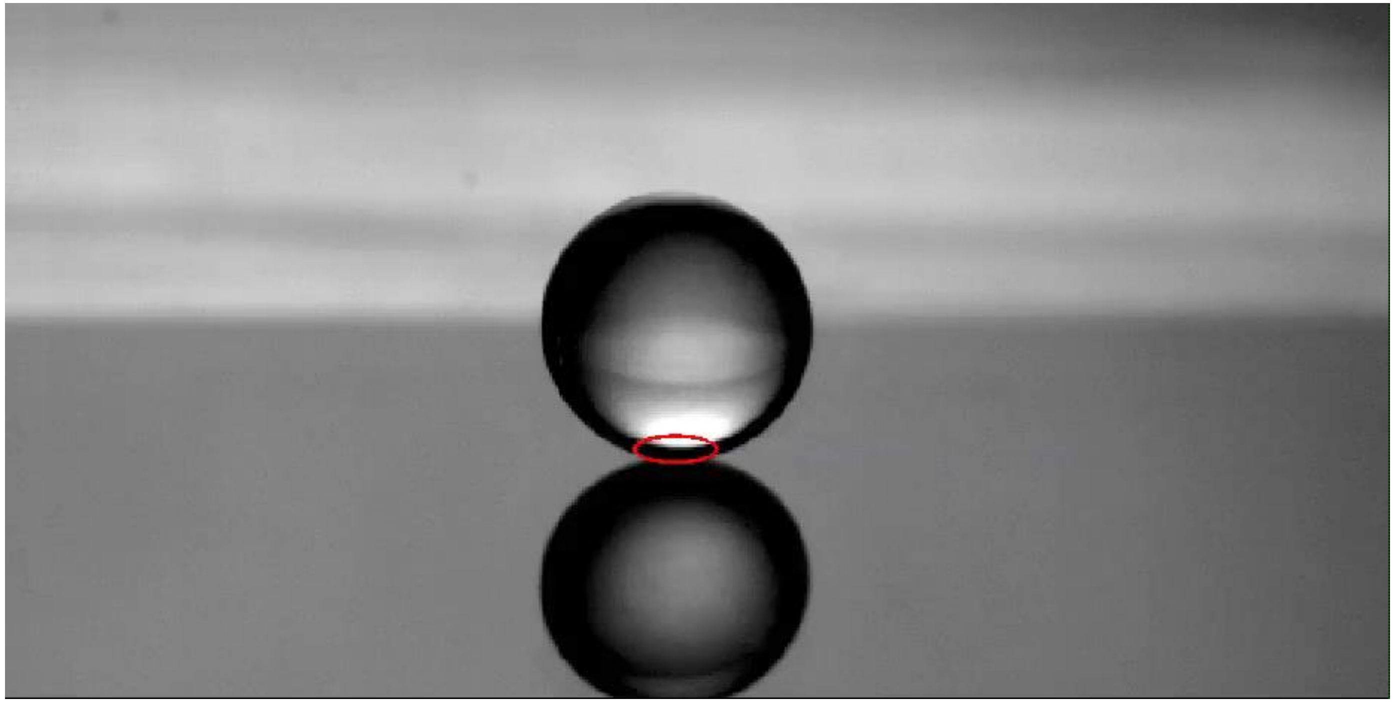

Heat transfer
Phase change
Impact dynamics
Impact Target
• Roughness
• Material
• Geometry
Spray Cooling

Frustrated Total Internal Reflection (FTIR)



Shirota, M., van Limbeek, M. A. J., Lohse, D., & Sun, C. (2017).
Measuring thin films using quantitative frustrated total internal reflection (FTIR).
The European Physical Journal E, *40*(5), 54.

Impact dynamics: short timescales



Ethanol drop impacting at U=2m/s on a cold sapphire surface

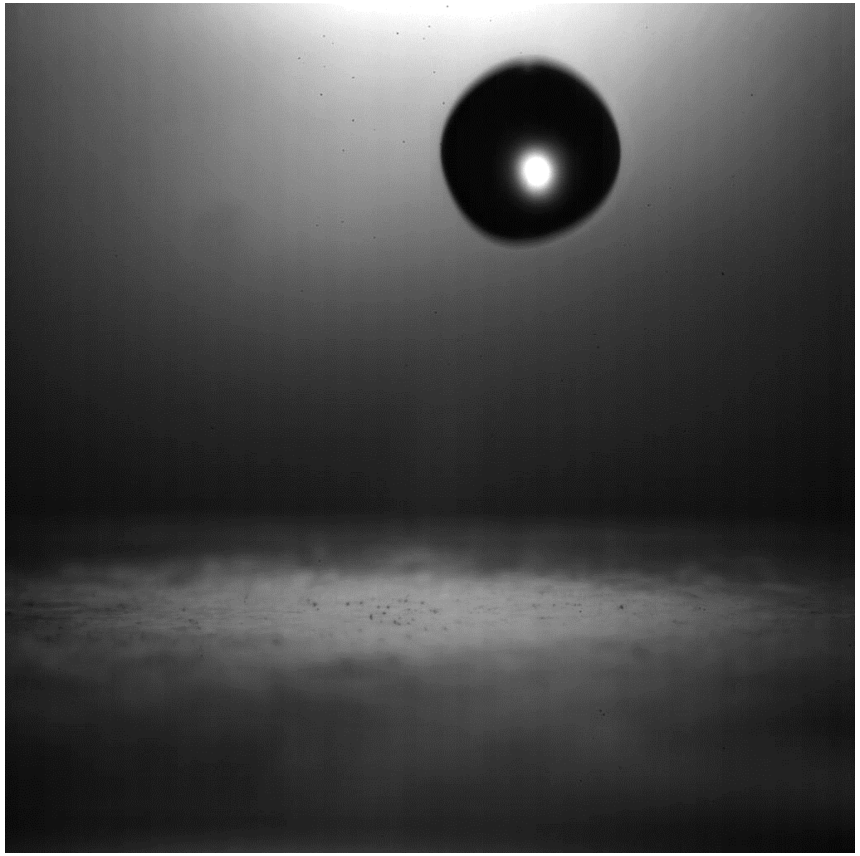
Shirota, Minori, et al. "Dynamic Leidenfrost effect: relevant time and length scales." *Physical review letters* 116.6 (2016): 064501.

Impact dynamics: heating

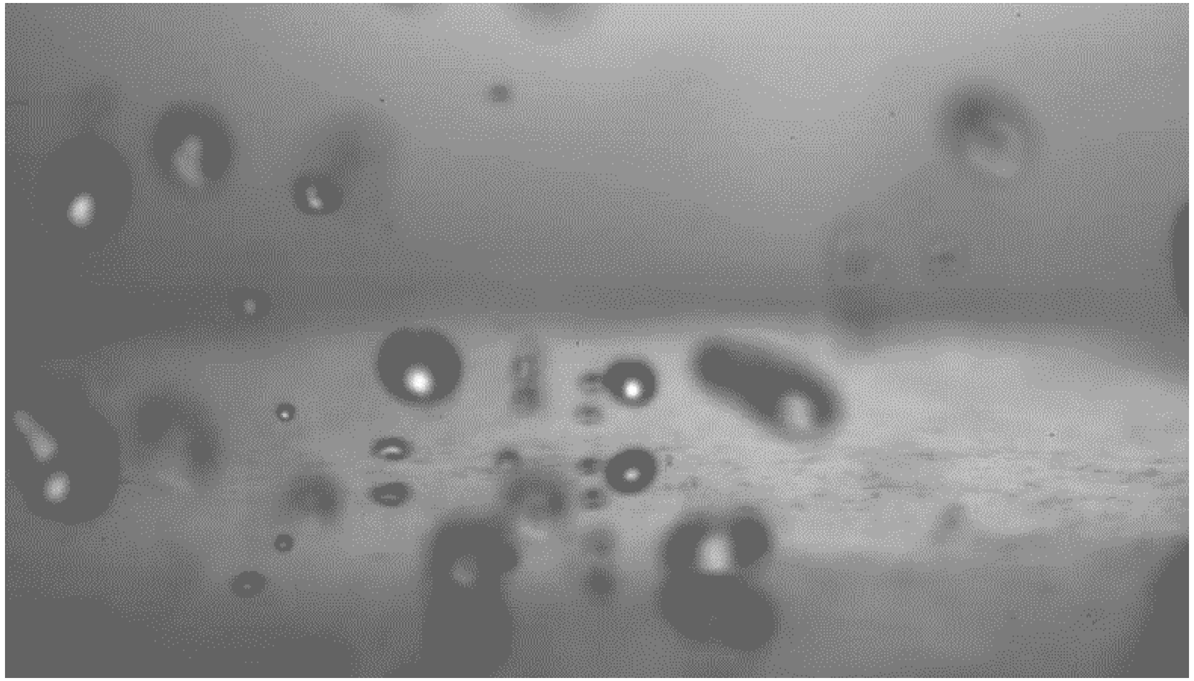
Liquid nitrogen on **heated** sapphire (smooth surface)

Two types of measurements

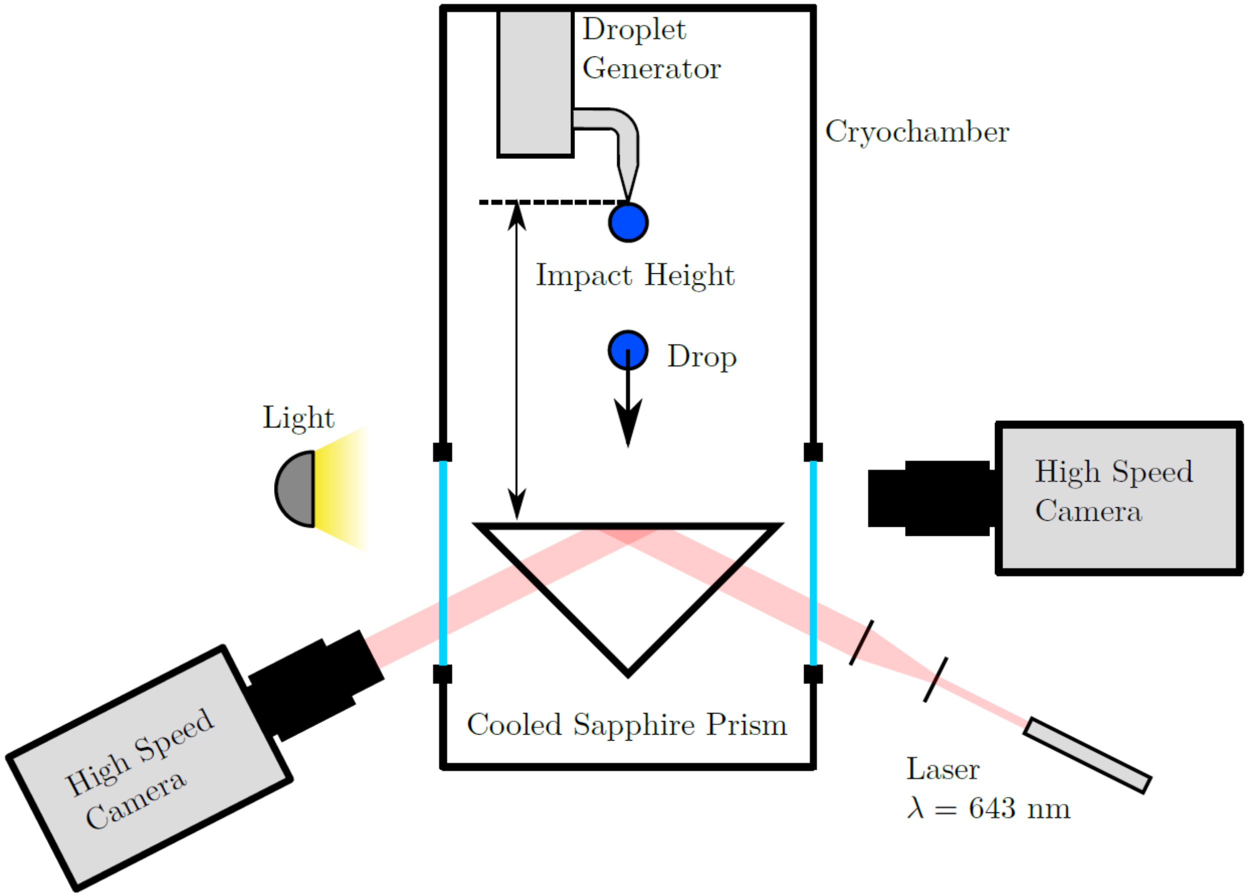
- Single drop



- Drop stream

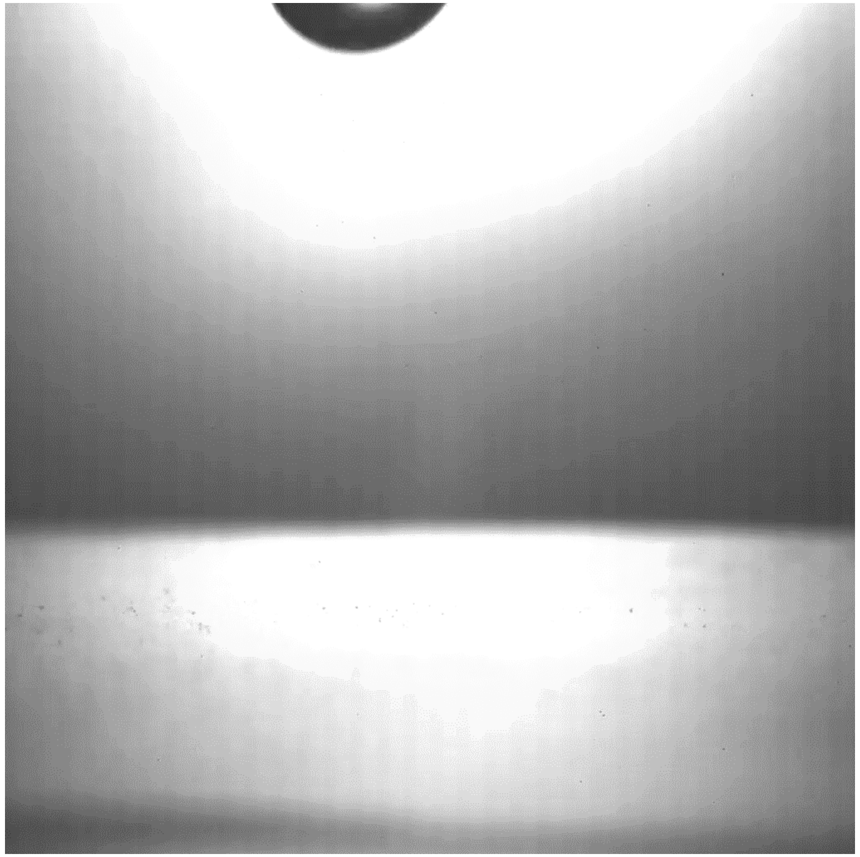


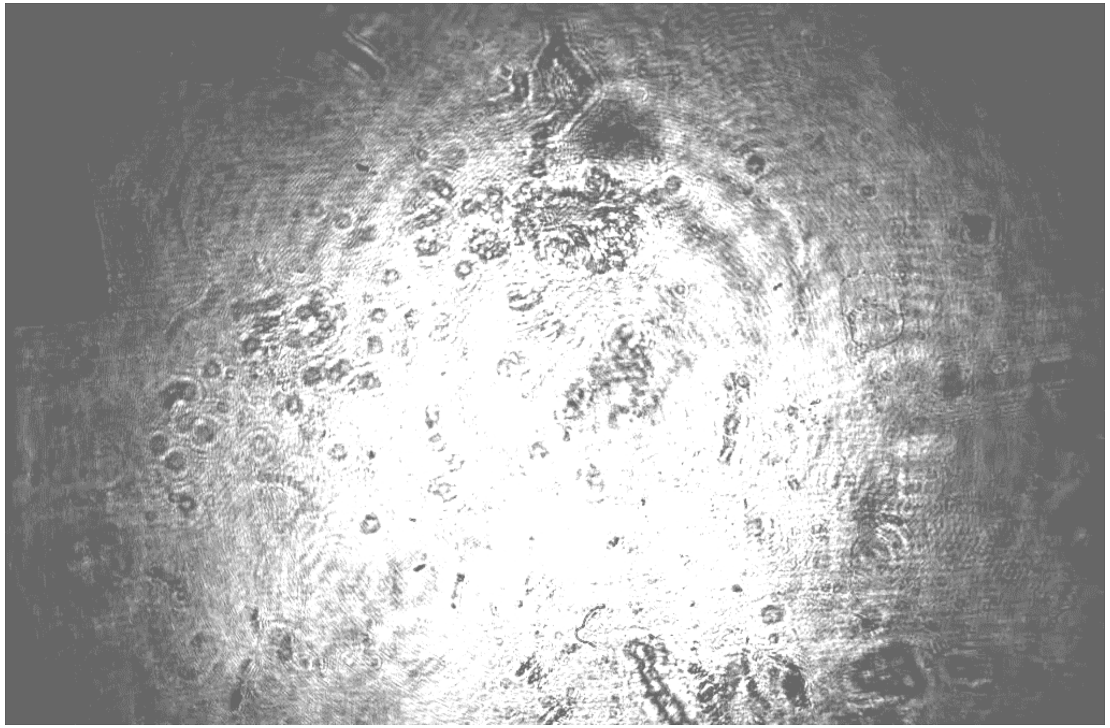
Experimental Set-up

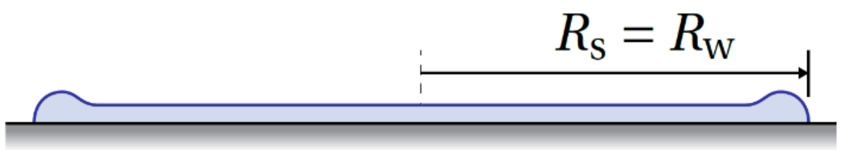


Results

U=1.3 m/s T=82 K





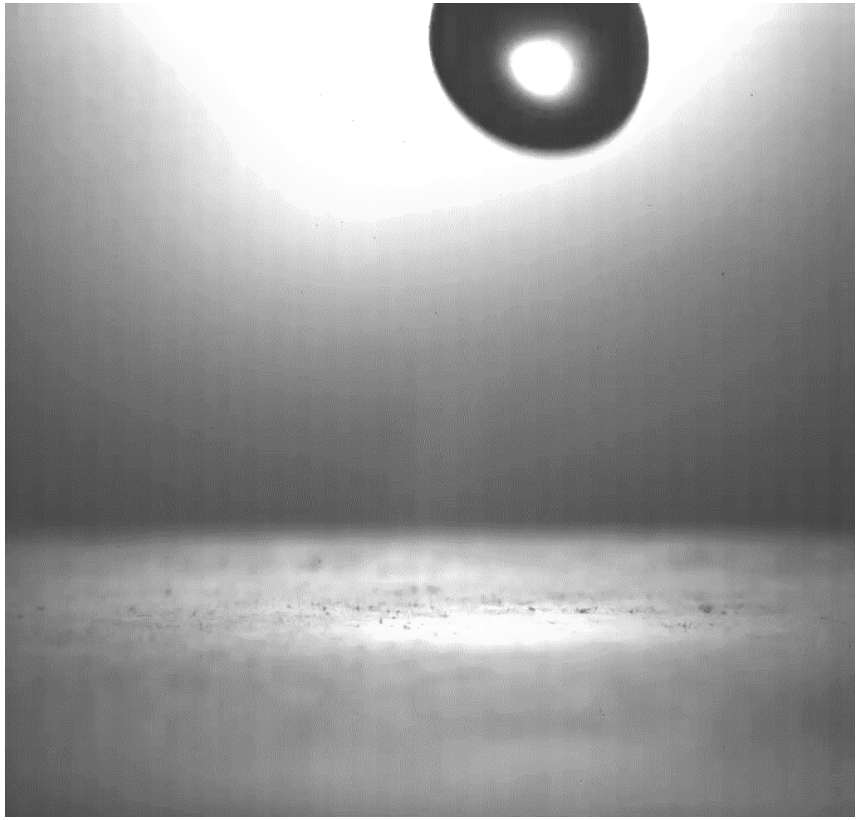


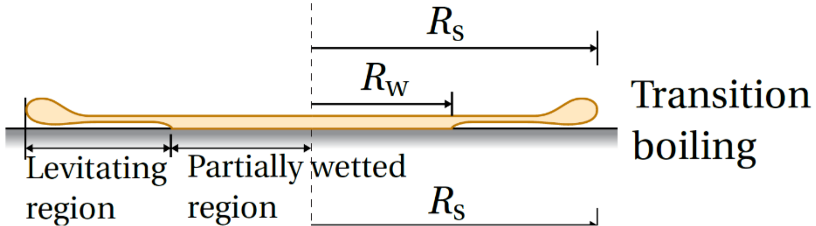
Contact boiling

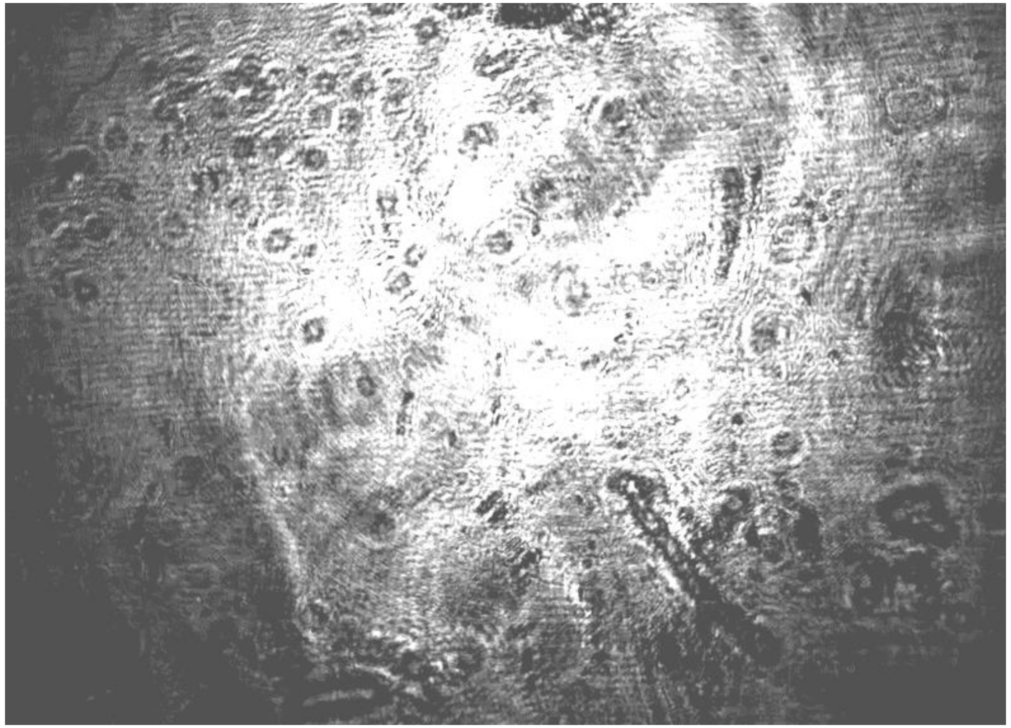
Slowed down 500x

Results
Increasing plate temperature

U=1.3 m/s T=92 K



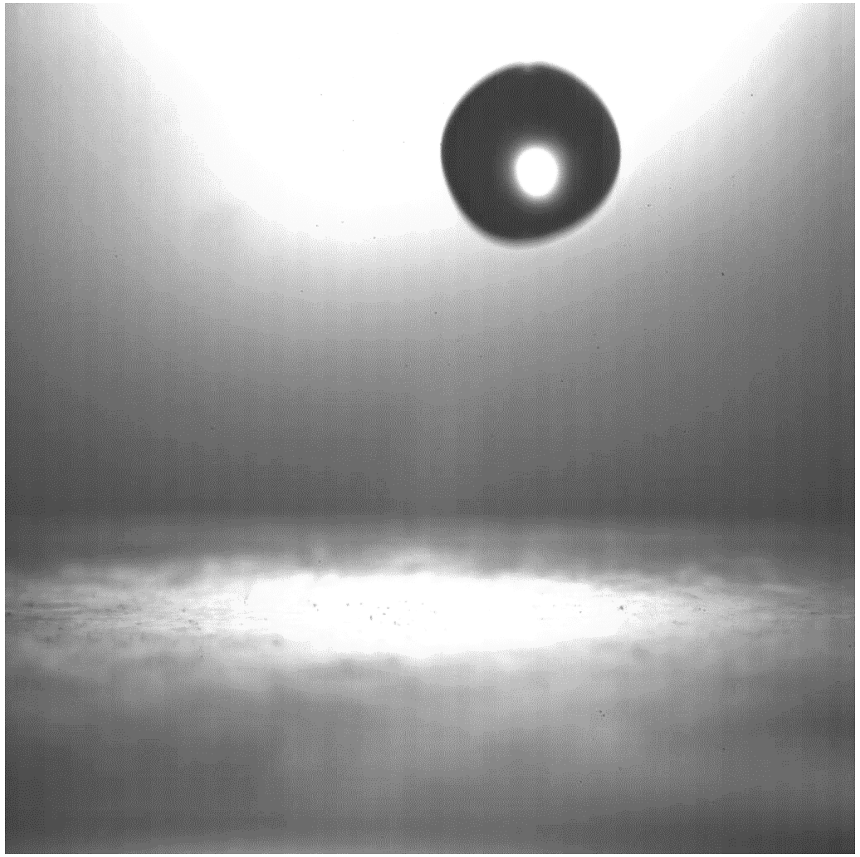


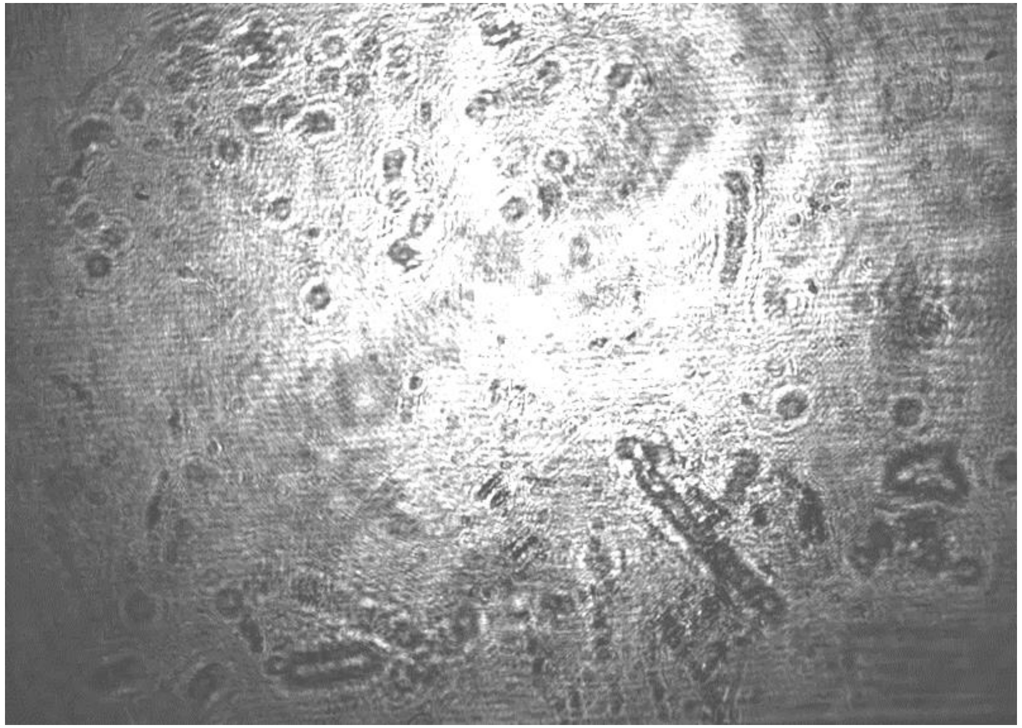


Slowed down 500x

Results
Increasing plate temperature

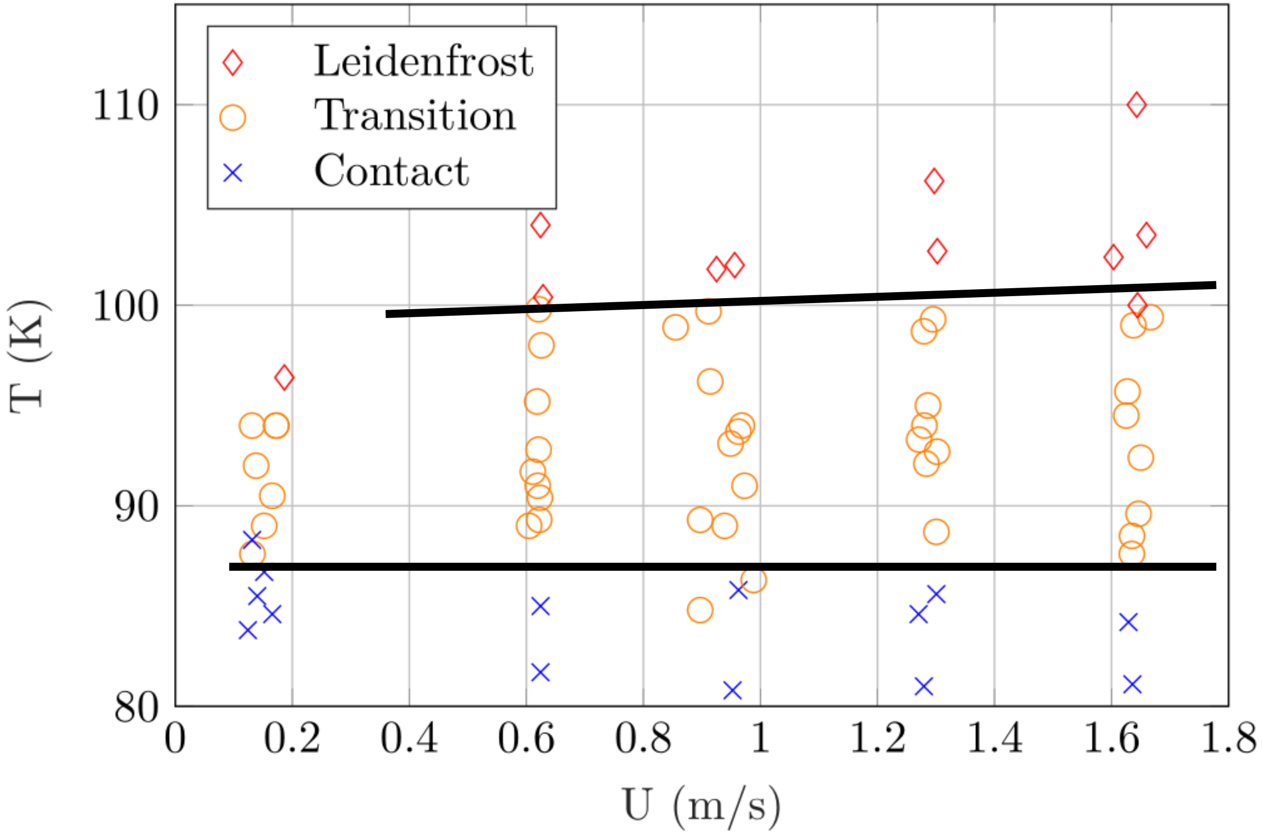
U=1.3 m/s T=102 K



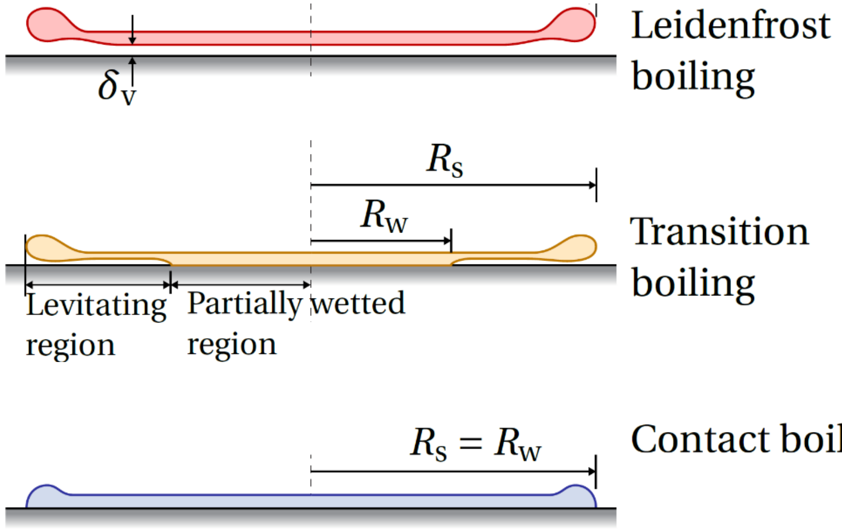


Slowed down 500x

Results

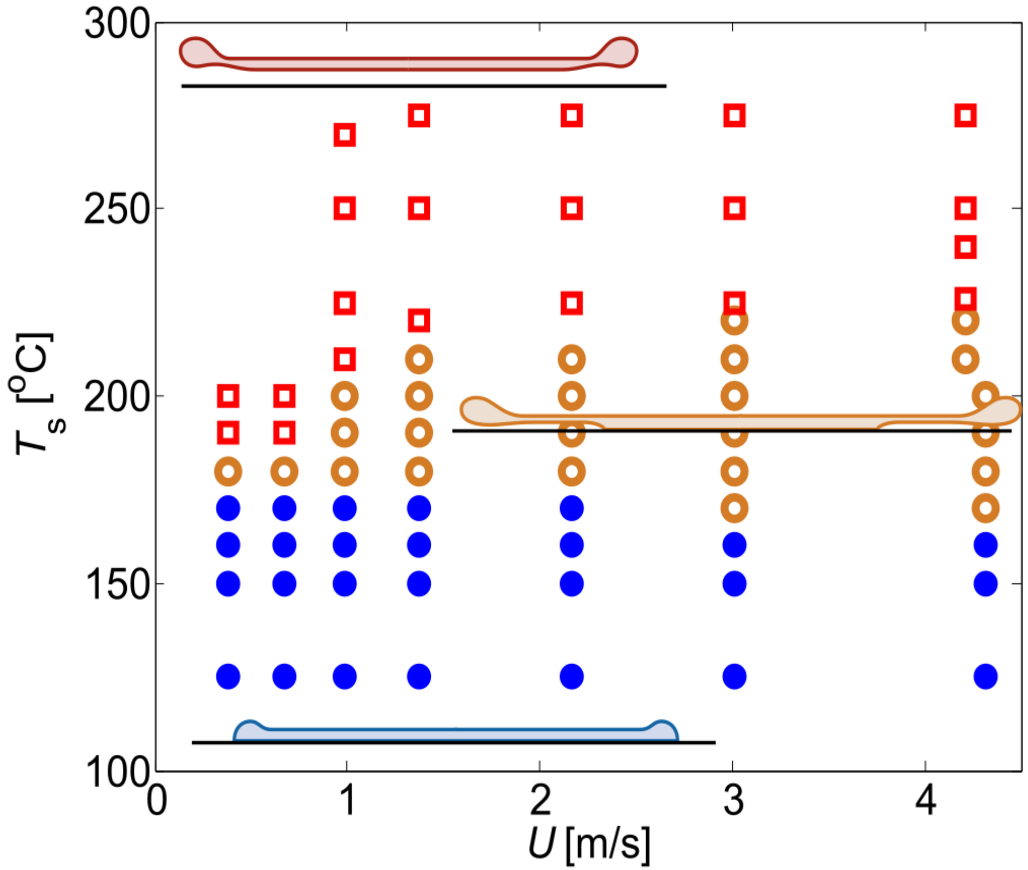


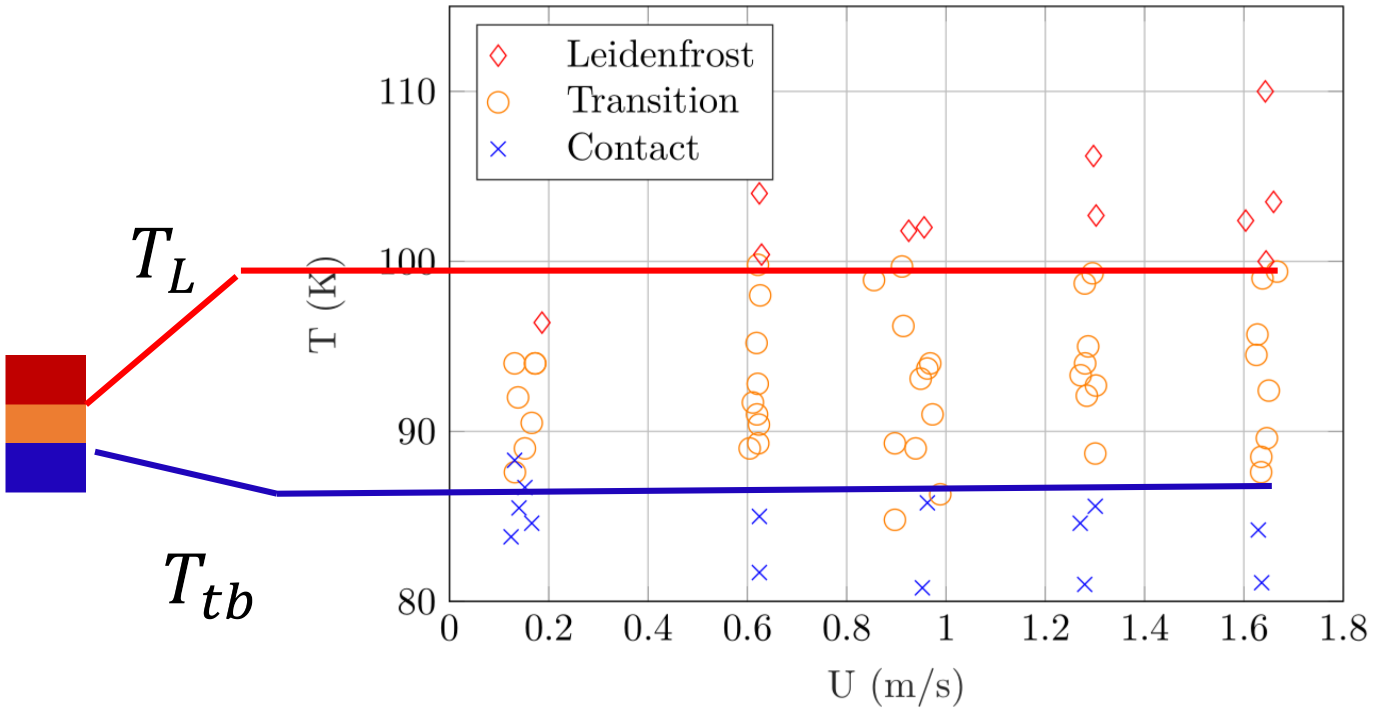
Leidenfrost
Transition
Contact
110
100
90
80
T (K)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
U (m/s)



Leidenfrost boiling
δ_v
R_s
R_w
Transition boiling
Levitating region
Partially wetted region
$R_s = R_w$
Contact boil

Ethanol vs LN_2





$$\Theta_{tb} \equiv \frac{T_L - T_{tb}}{T_{crit}}$$

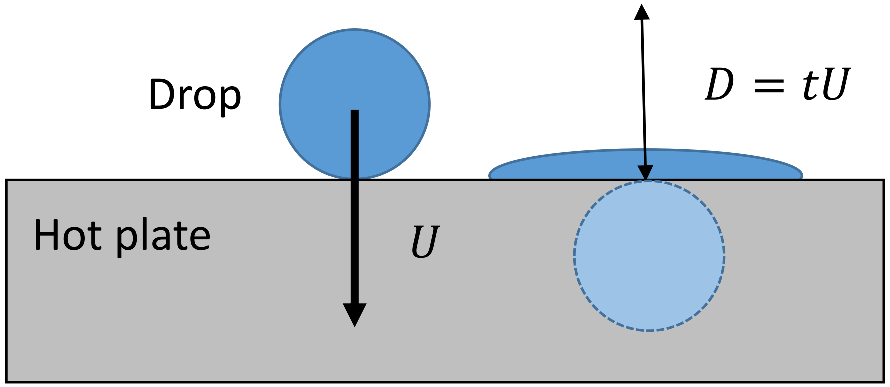
Rescaling

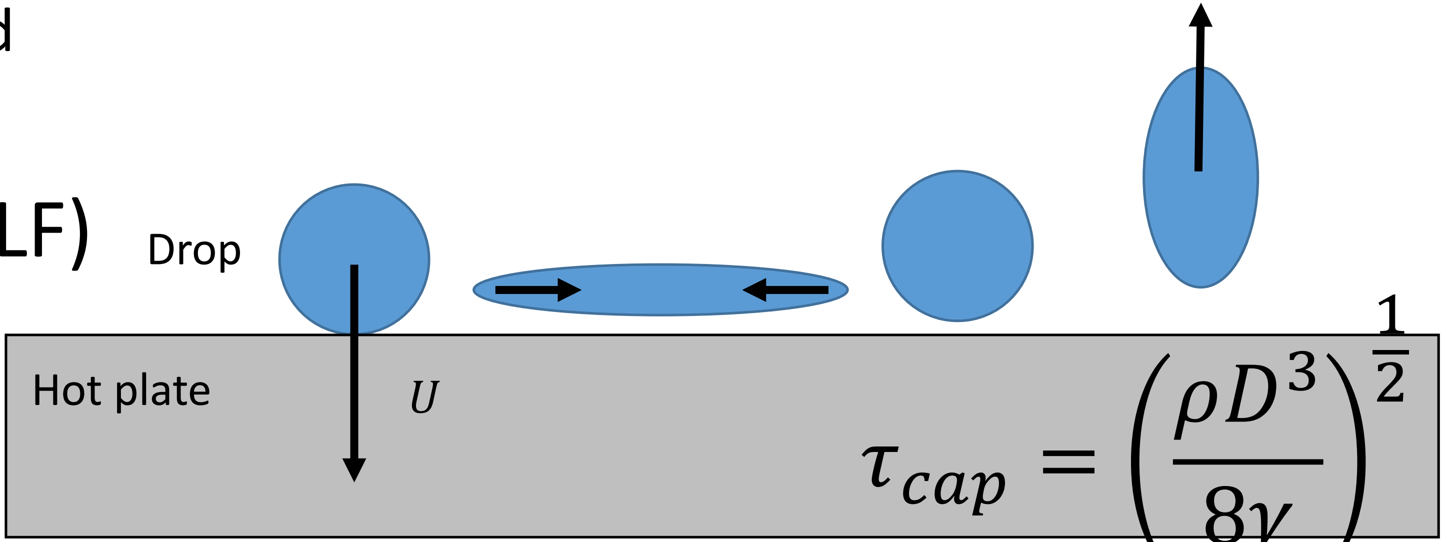
	Nitrogen	Water	Water	Ethanol	FC84	Acetone	Heptane	Heptane
T_{sat} [K]	77	373	373	351	351	329	371	371
T_{tb} [K]	86	493	413	423	403	403	433	433
T_L [K]	100	573	493	493	473	458	473	483
T_c [K]	126	647	647	516	478	508	540	540
Θ_{tb} [-]	0.11	0.12	0.12	0.14	0.15	0.11	0.07	0.09

Exp Data from multiple referenced papers

Impact timescale

- How long does the drop take heat?
  - Impact timescale $\tau = D/U$
  - Contact time (non LF)
    drop sticks until evaporated
  - Capillary timescale (LF)





$$\tau_{cap} = \left(\frac{\rho D^3}{8\gamma}\right)^{\frac{1}{2}}$$

Dominant heat transfer mechanism

$\dot{Q}_{cond}/\dot{Q}_{evap}$

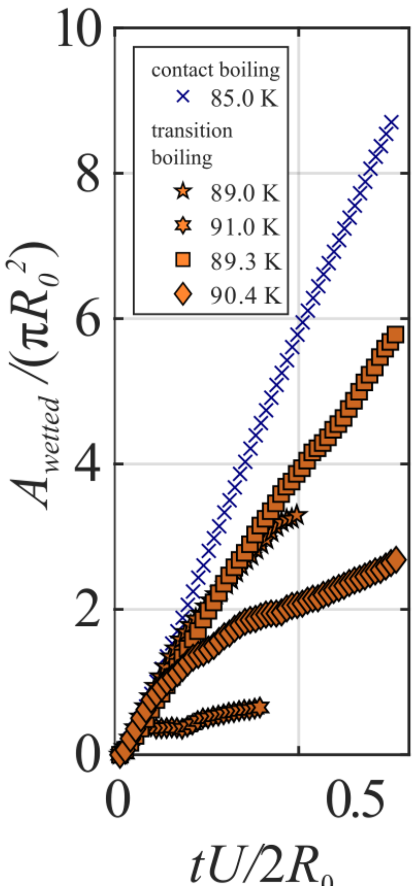
- $\dot{Q}_{cond} \sim A_{wet}\, k_l \frac{T_{drop} - T_s}{\sqrt{\alpha_l t}}$

- $\dot{Q}_{evap} \sim L_{cl} \dot{Q}_{cl} \approx L_{cl} 0.2\, (T_{drop} - T_s)$ [1]

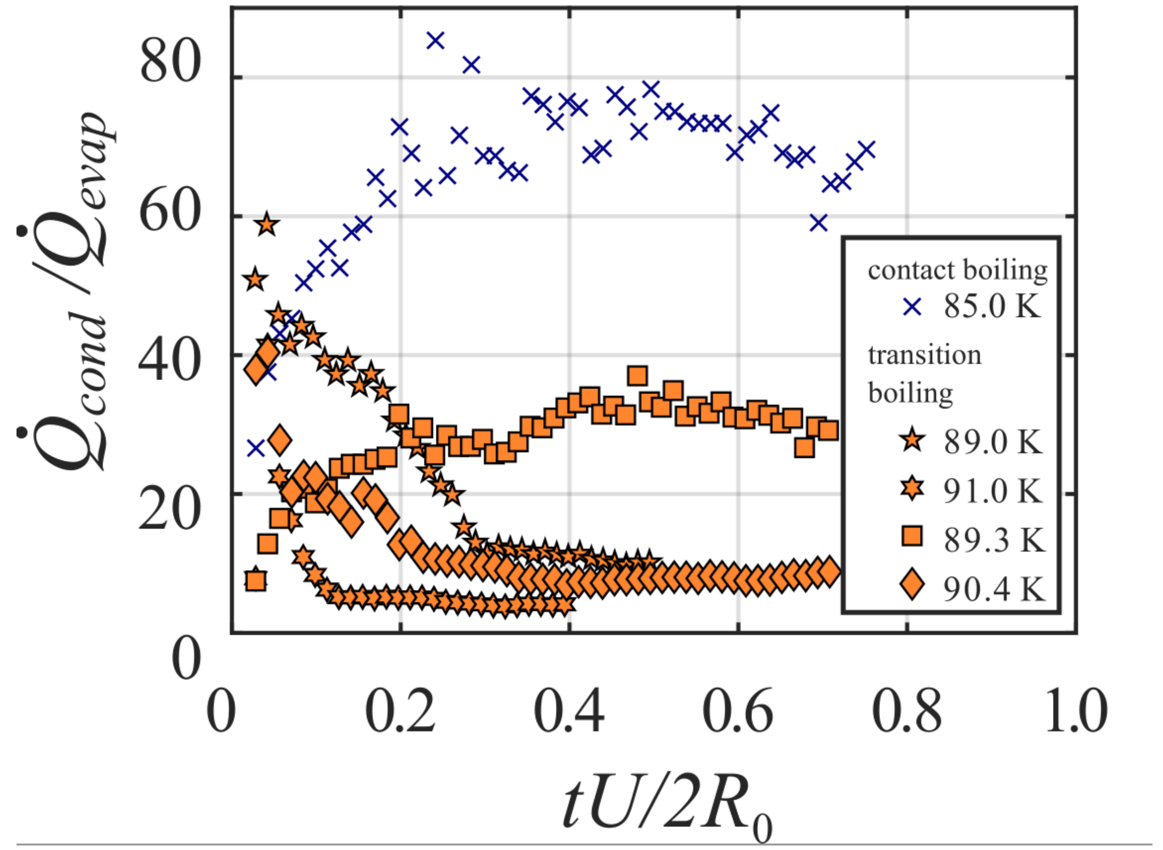
- $\frac{\dot{Q}_{cond}}{\dot{Q}_{evap}} \sim \frac{A_{wet}}{L_{cl}} \frac{k_l}{0.2\sqrt{\alpha_l t}}$

[1] S. Herbert, S. Fischer, T. Gambaryan-Roisman, and P. Stephan, **Local heat transfer and phase change phenomena during single drop impingement on a hot surface,** *IJHMT, vol. 61,* 2013

Area vs contact line



Dominant heat transfer mechanism



Role of impact target: thermal properties

Is the target isothermal during the impact?

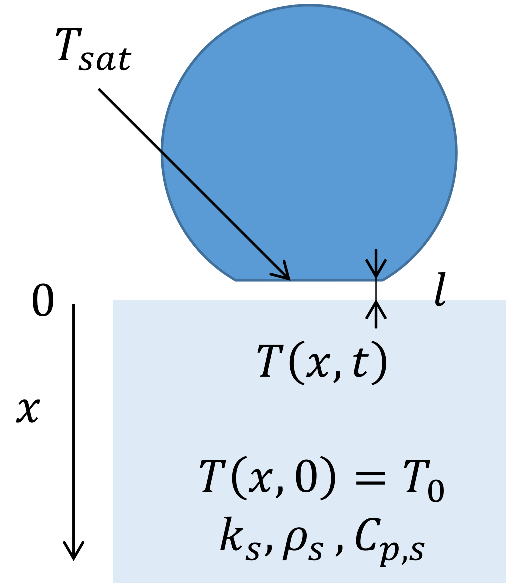
Thermal timescale

- 1D Heat equation

$$\partial_t T = \alpha \partial_x^2 T$$

- Heat flux across the vapour layer

$$k_s \partial_x T = h(T - T_{sat})$$

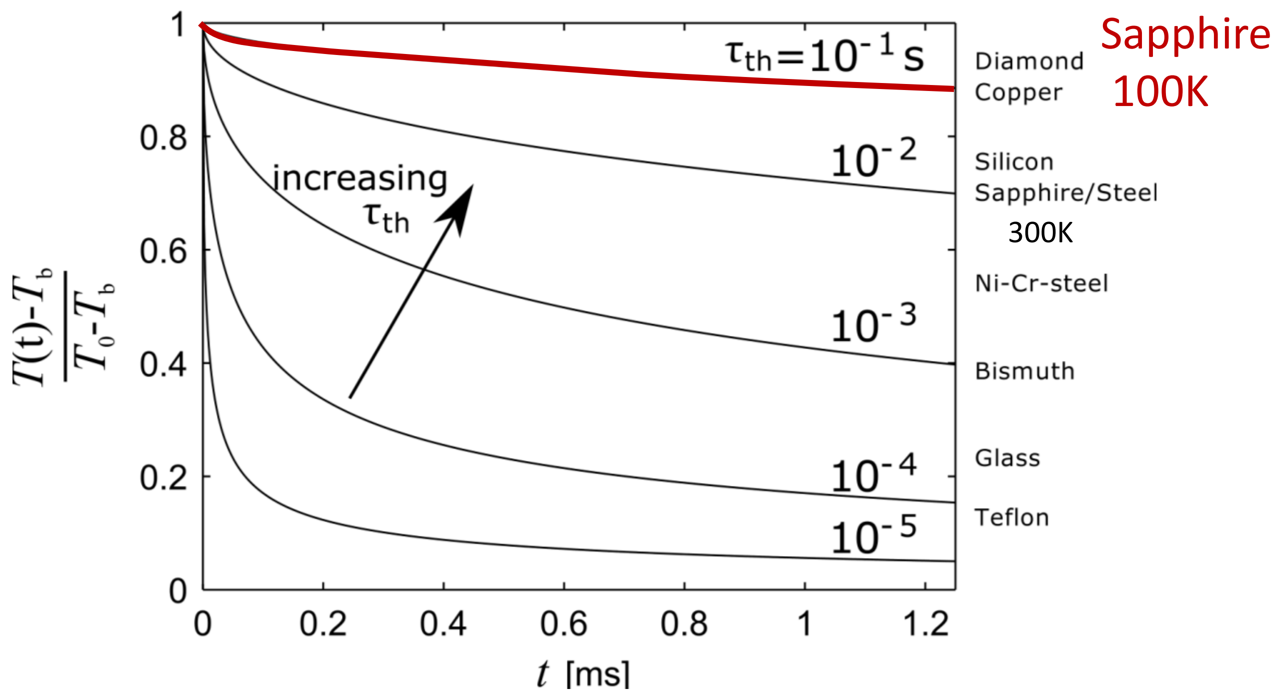


$$\Theta = \exp\left(\frac{t}{\tau_{th}}\right) \operatorname{erfc}\left(\sqrt{t/\tau_{th}}\right)$$

where $\Theta = \frac{T_{x=0} - T_{sat}}{T_0 - T_{sat}}$ and $\tau_{th} = k_s \rho_s C_{p,s} h^{-2}$

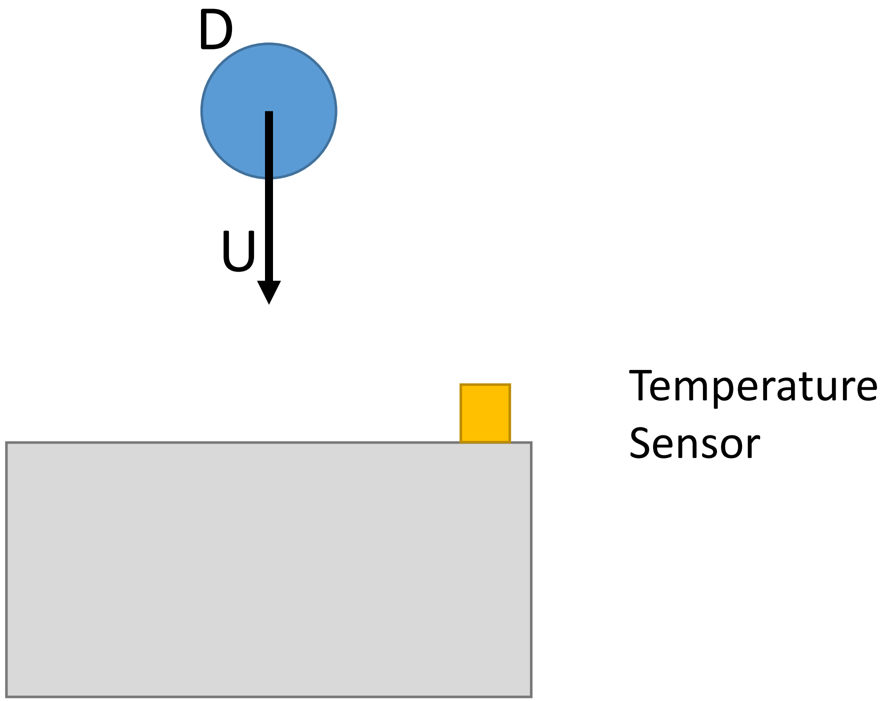
Thermal properties of impactor

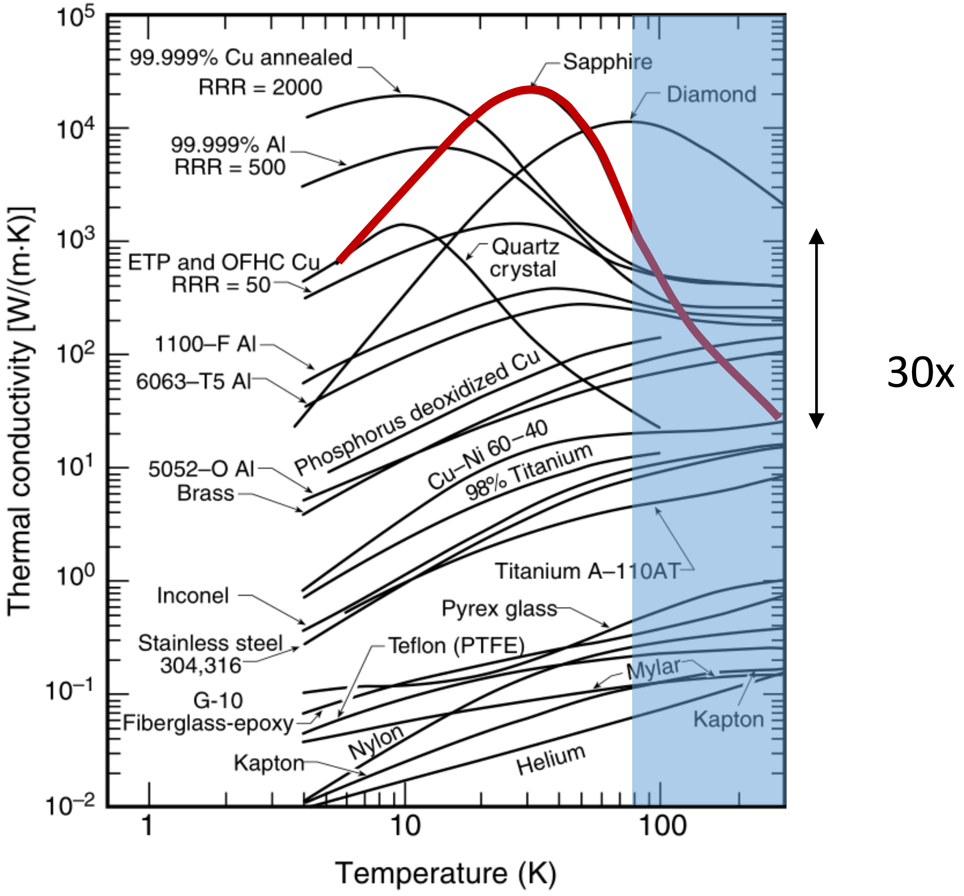
- Thermal timescale
  $$k\rho C_p/h^2 \sim 0.1\ \mathrm{s} \ll D/U$$
- **Isothermal behaviour**



MAJ van Limbeek et al. *Vapour cooling of poorly conducting hot substrates increases the dynamic Leidenfrost temperature* Int J Heat&Mass Transfer 97 (2016): 101-109

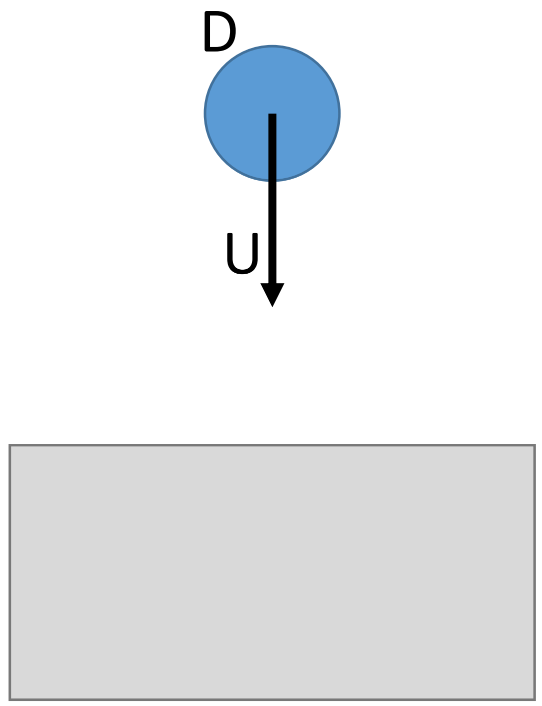
Test setup



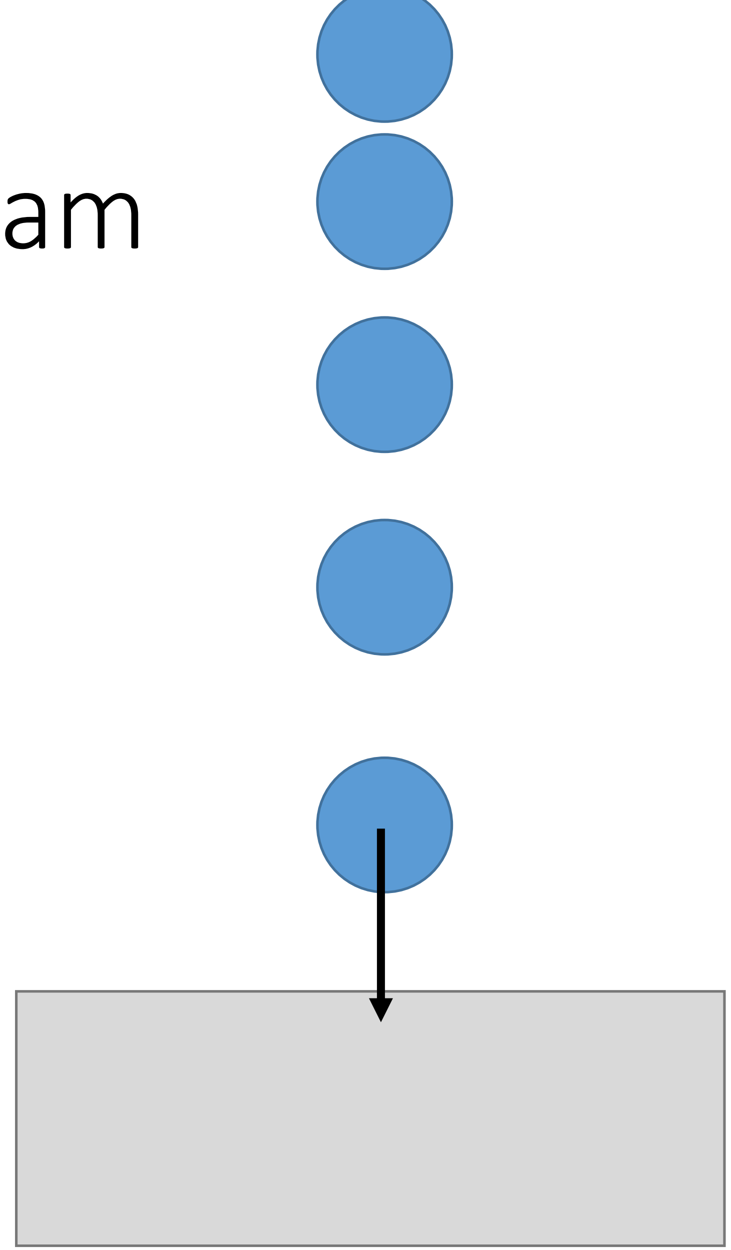


J.W. Ekins *Experimental Techniques for Low-Temperature Measurements* Oxford University Press 2006

Droplet stream

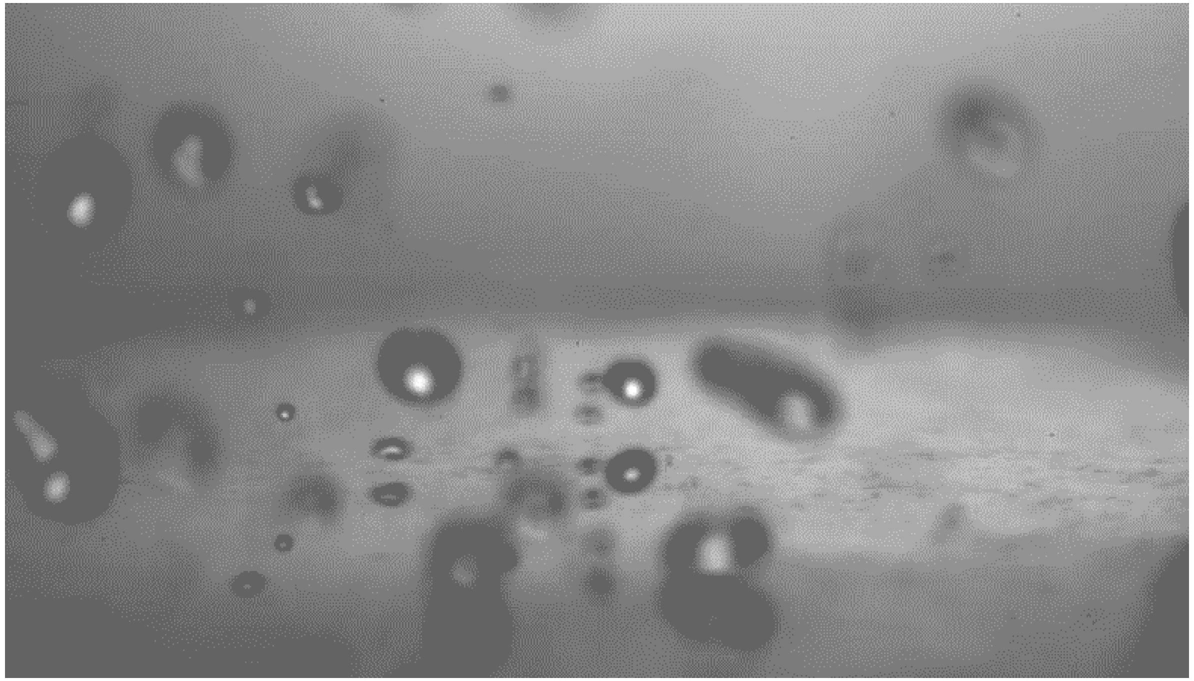


Droplet stream

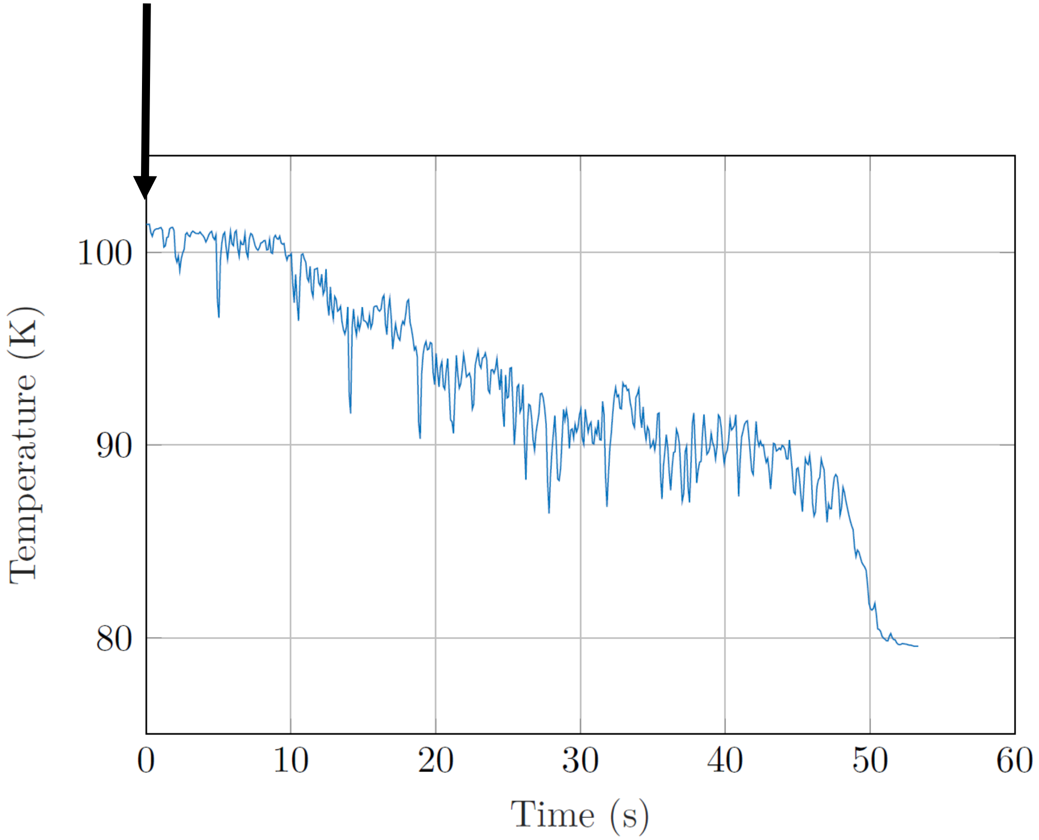


Results

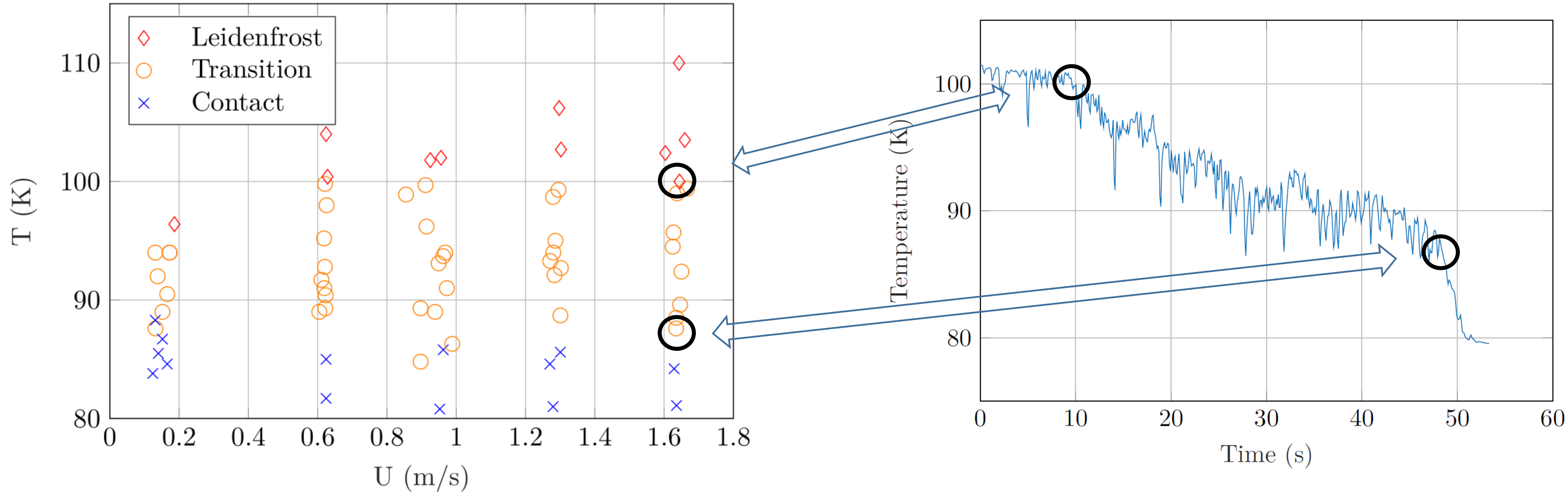
U=1.6 m/s



Slowdown 5x

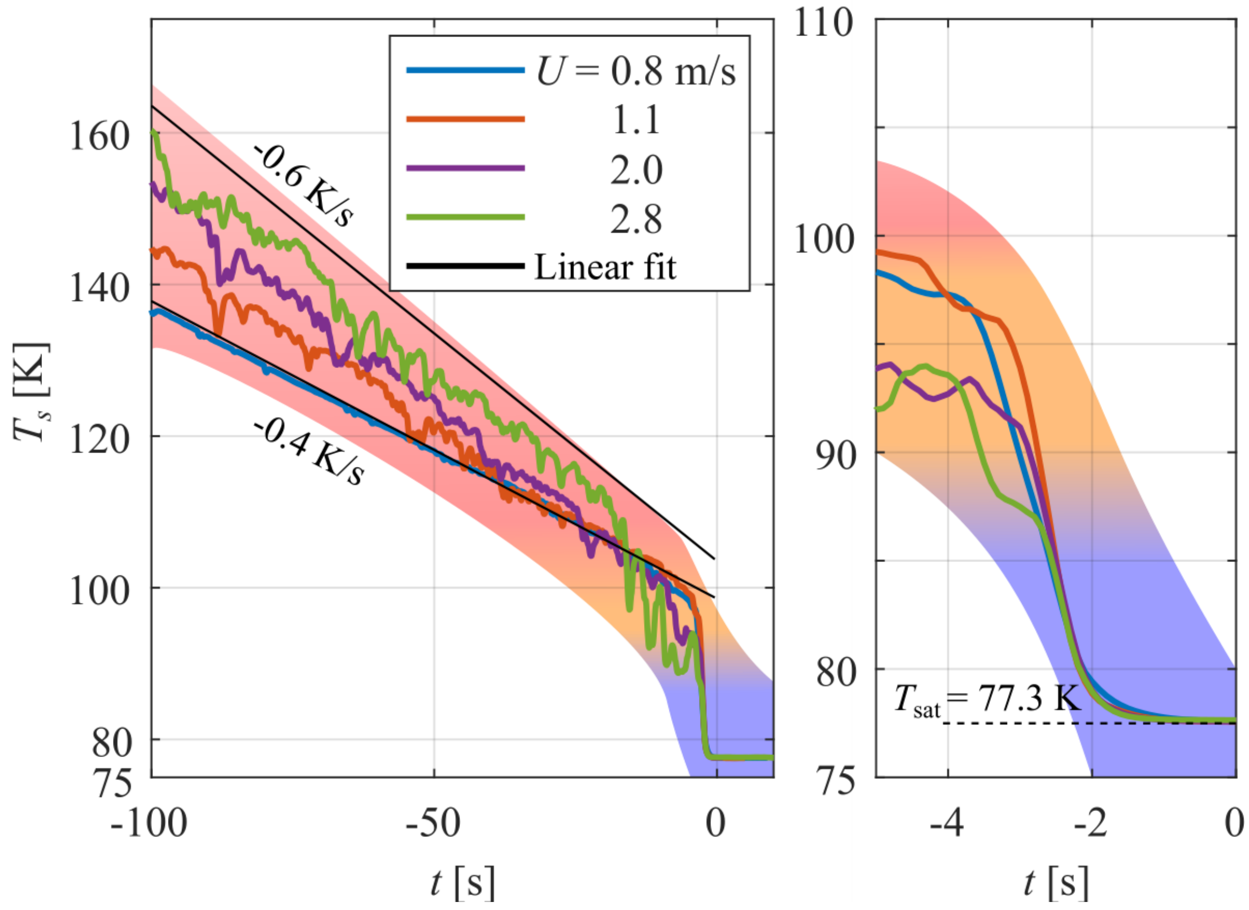


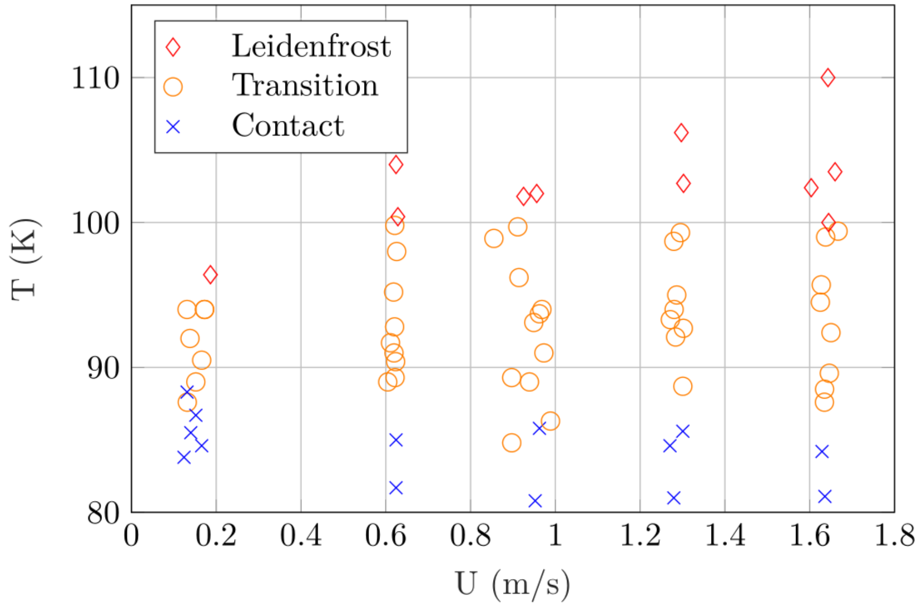
Results



Leidenfrost
Transition
Contact
T (K)
U (m/s)
110
100
90
80
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Temperature (K)
Time (s)
100
90
80
0
10
20
30
40
50
60

Varying the velocity Zoom



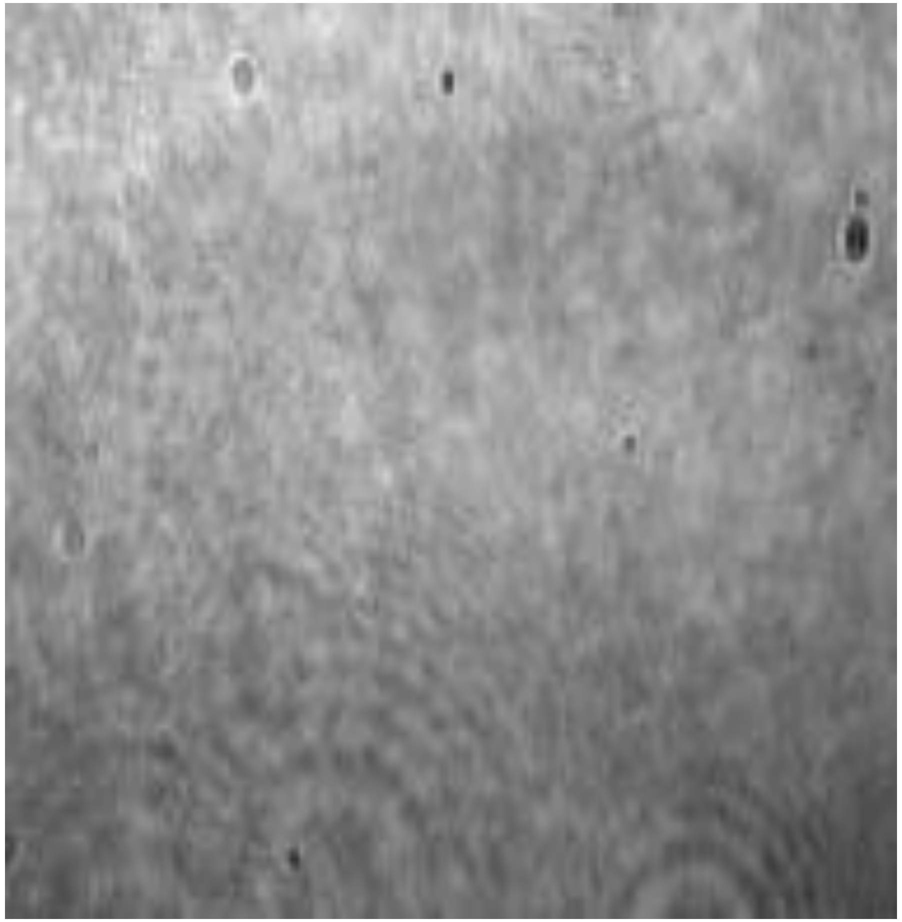


Thermal effect of plate changes T_L

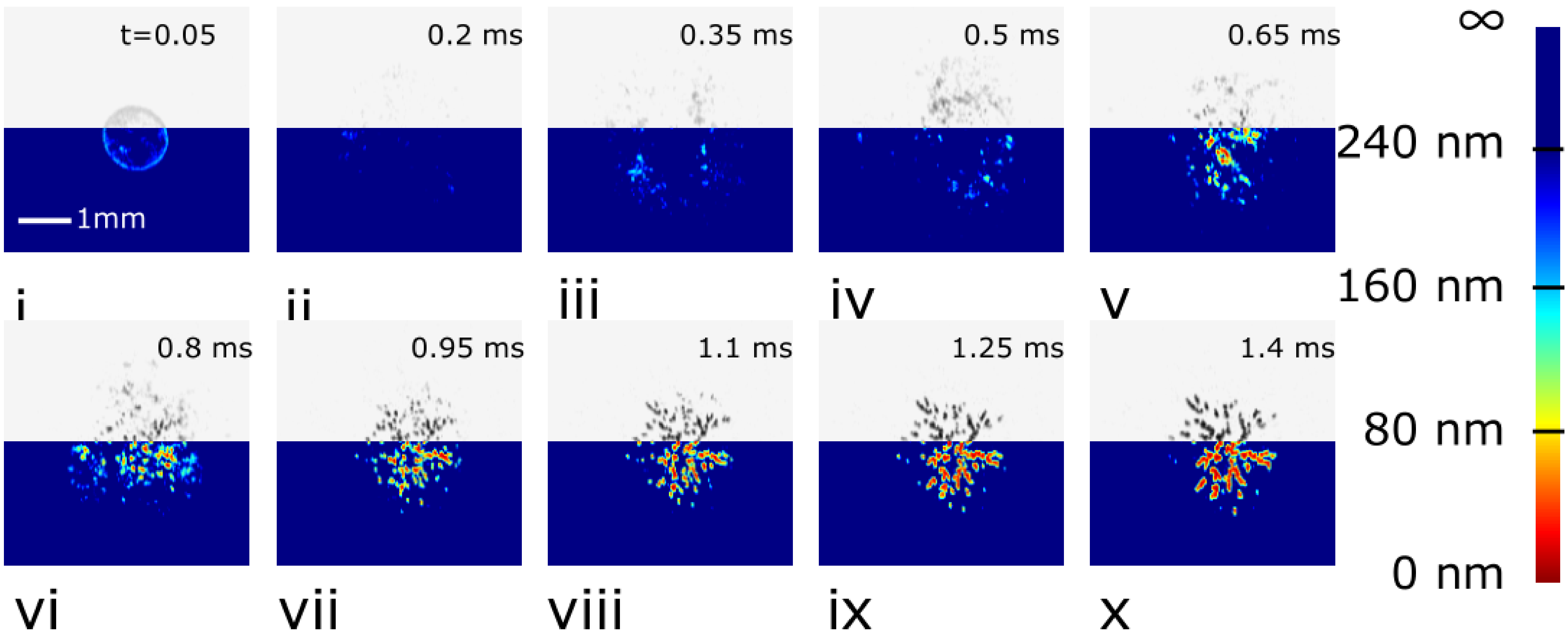
Solid properties

Property	Sapphire 80K	Sapphire 300K	Glass 300K	units
Density ρ_s	4000	4000	2520	kg/m^3
Specific heat $C_{p,s}$	100	776	816	kJ/kg K
Thermal conductivity k_s	1000	32	1	W/K m
Thermal diffusivity $\alpha_s = {}^{k_s}/_{\rho_s C_{p,s}}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-5}$	$4 \cdot 10^{-7}$	m^2/s
Thermal timescale τ_{th}	100	15	3	ms

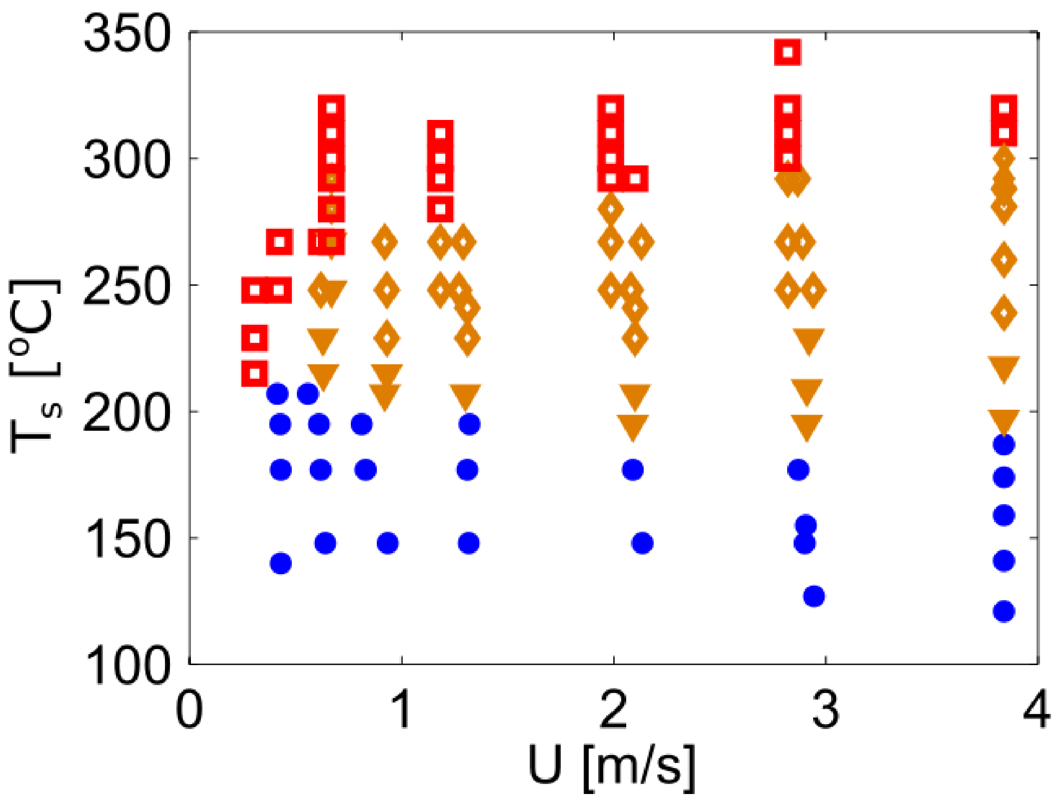
Delayed touchdown on glass



T=292^{o}C U=3.8m/s


t=0.05
1mm
i
0.2 ms
ii
0.35 ms
iii
0.5 ms
iv
0.65 ms
v
0.8 ms
vi
0.95 ms
vii
1.1 ms
viii
1.25 ms
ix
1.4 ms
x
∞
240 nm
160 nm
80 nm
0 nm

Glass Phase diagram



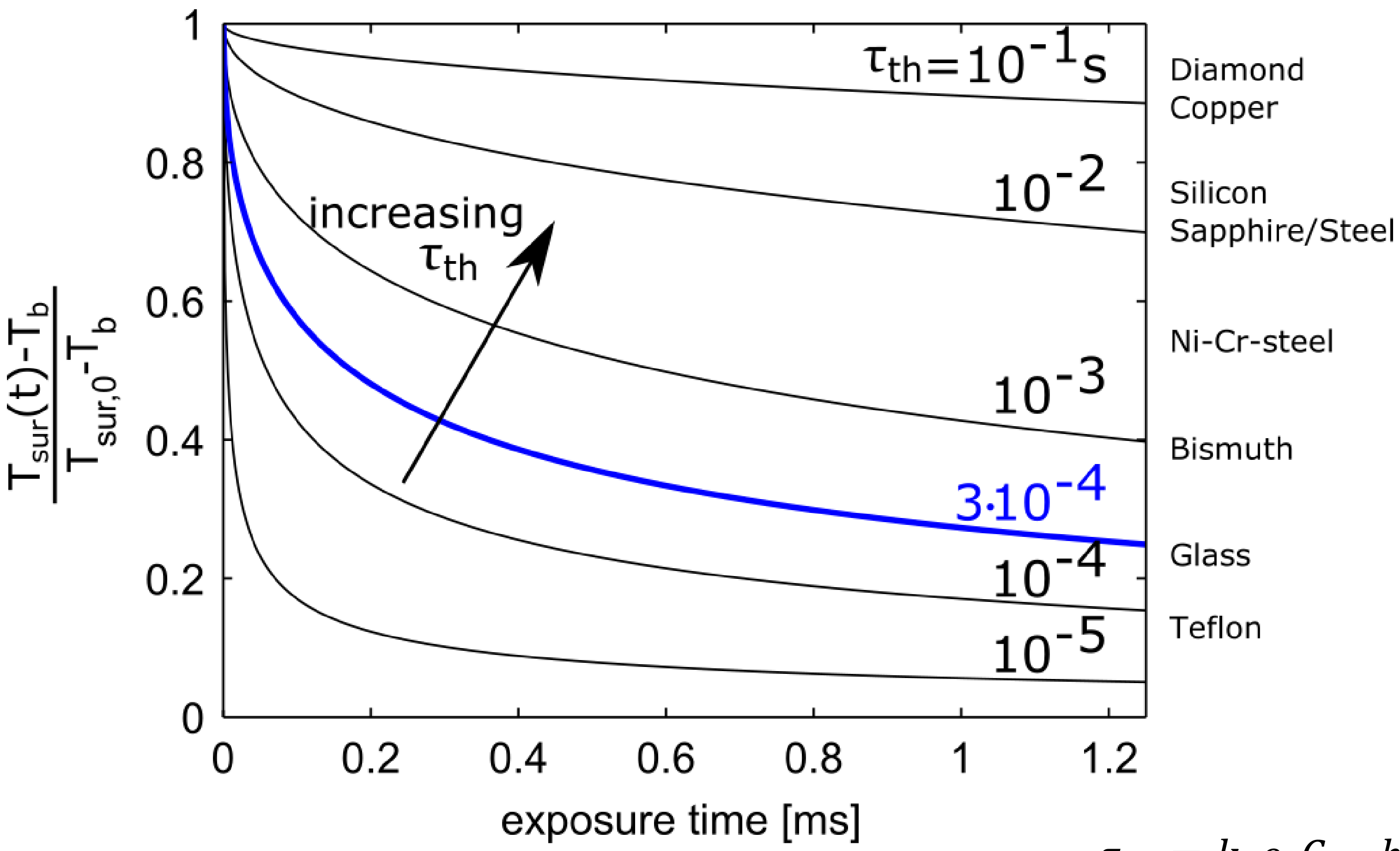
Leidenfrost boiling

Transition boiling

Contact boiling

van Limbeek, Shirota, Sleutel, Prosperetti, Sun and Lohse, *IJHMT* 2016

Surface cooling



$$\tau_{th} = k_s \rho_s C_{p,s}\, h^{-2}$$

Competition of two timescales

- Impact timescale $\tau_{imp} = \frac{\text{Drop diameter}}{\text{Impact velocity}} \approx 1\text{ ms}$

represents the contact or residence
time of the drop near the surface

- Cooling effects become relevant when

$$\tau_{th} \approx \tau_{imp}$$

which is the case for a glass surface:
0.3 ms ≈1 ms

Micro droplet

T=265^{o}C

T=305^{o}C

U=10 m/s, slowed 20k

Conclusion/Overview

- We studied the impact of liquid nitrogen drops and obtained the phase diagram for the dynamic Leidenfrost effect

- The high thermal conductivity of the sapphire impact target enables us to measure the temperature of the plate during spray cooling and relate it to the wetting behavior using FTIR imaging.

- A strong correlation between the cooling of the sapphire and the wetting behavior was observed.

- Conductive cooling is stronger than evaporation