Impact characteristics of liquid nitrogen droplets

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Spray cooling

\[ \dot{Q} \? \]

Drop

Hot plate

\[ U \]
Heat transfer

Impact Target
- Roughness
- Material
- Geometry

Impact dynamics

Phase change

Spray Cooling
Frustrated Total Internal Reflection (FTIR)

Impact dynamics: short timescales

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

Impact dynamics: heating

Liquid nitrogen on heated sapphire (smooth surface)
Two types of measurements

• Single drop

• Drop stream
Experimental Set-up
Results

$U=1.3 \text{ m/s } T=82 \text{ K}$

Contact boiling

Slowed down 500x
Results
Increasing plate temperature

$U=1.3 \text{ m/s } T=92 \text{ K}$

Slowed down 500x
Results
Increasing plate temperature

$U=1.3 \text{ m/s } T=102 \text{ K}$
Results
Ethanol vs LN$_2$

$$T_{tb} \equiv \frac{T_L - T_{tb}}{T_{crit}}$$
# Rescaling

Exp Data from multiple referenced papers

<table>
<thead>
<tr>
<th></th>
<th>Nitrogen</th>
<th>Water</th>
<th>Water</th>
<th>Ethanol</th>
<th>FC84</th>
<th>Acetone</th>
<th>Heptane</th>
<th>Heptane</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{sat}$ [K]</td>
<td>77</td>
<td>373</td>
<td>373</td>
<td>351</td>
<td>351</td>
<td>329</td>
<td>371</td>
<td>371</td>
</tr>
<tr>
<td>$T_{lb}$ [K]</td>
<td>86</td>
<td>493</td>
<td>413</td>
<td>423</td>
<td>403</td>
<td>403</td>
<td>433</td>
<td>433</td>
</tr>
<tr>
<td>$T_L$ [K]</td>
<td>100</td>
<td>573</td>
<td>493</td>
<td>493</td>
<td>473</td>
<td>458</td>
<td>473</td>
<td>483</td>
</tr>
<tr>
<td>$T_c$ [K]</td>
<td>126</td>
<td>647</td>
<td>647</td>
<td>516</td>
<td>478</td>
<td>508</td>
<td>540</td>
<td>540</td>
</tr>
<tr>
<td>$\Theta_{lb}$ [-]</td>
<td>0.11</td>
<td>0.12</td>
<td>0.12</td>
<td>0.14</td>
<td>0.15</td>
<td>0.11</td>
<td>0.07</td>
<td>0.09</td>
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</table>
Impact timescale

• How long does the drop take heat?
  • Impact timescale $\tau = \frac{D}{U}$

• 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
\[ \frac{\dot{Q}_{\text{cond}}}{\dot{Q}_{\text{evap}}} \]

- \[ \dot{Q}_{\text{cond}} \sim A_{\text{wet}} \kappa_l \frac{T_{\text{drop}} - T_s}{\sqrt{\alpha_l t}} \]

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

\[ \frac{\dot{Q}_{\text{cond}}}{\dot{Q}_{\text{evap}}} \sim \frac{A_{\text{wet}} \kappa_l}{L_{cl}} 0.2 \sqrt{\alpha_l t} \]

Area vs contact line
Dominant heat transfer mechanism

![Graph showing heat transfer mechanism](image)
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
  \[ k_s \partial_x T = h(T - T_{sat}) \]

\[ \Theta = \exp \left( \frac{t}{\tau_{th}} \right) \text{erfc} \left( \sqrt{\frac{t}{\tau_{th}}} \right) \]

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
  \[ \frac{k\rho C_p}{h^2} \sim 0.1 \text{ s} \ll \frac{D}{U} \]

• Isothermal behaviour

Test setup

Temperature Sensor

Droplet stream
Droplet stream
Results

$U = 1.6 \text{ m/s}$

Slowdown 5x
Results
Varying the velocity Zoom
Thermal effect of plate changes $T_L$
## Solid properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Sapphire 80K</th>
<th>Sapphire 300K</th>
<th>Glass 300K</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density $\rho_s$</td>
<td>4000</td>
<td>4000</td>
<td>2520</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Specific heat $C_{p,s}$</td>
<td>100</td>
<td>776</td>
<td>816</td>
<td>kJ/kg K</td>
</tr>
<tr>
<td>Thermal conductivity $k_S$</td>
<td>1000</td>
<td>32</td>
<td>1</td>
<td>W/K m</td>
</tr>
<tr>
<td>Thermal diffusivity $\alpha_s$</td>
<td>$1\cdot10^{-3}$</td>
<td>$1\cdot10^{-5}$</td>
<td>$4\cdot10^{-7}$</td>
<td>m²/s</td>
</tr>
<tr>
<td>Thermal timescale $\tau_{th}$</td>
<td>100</td>
<td>15</td>
<td>3</td>
<td>ms</td>
</tr>
</tbody>
</table>
Delayed touchdown on glass

T=292°C U=3.8m/s
Glass Phase diagram

Surface cooling

\[ \tau_{th} = k_s \rho_s C_{p_s} h^{-2} \]
Competition of two timescales

- Impact timescale $\tau_{imp} = \approx 1 \text{ ms}$ 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: $0.3 \text{ ms} \approx 1 \text{ ms}$.
Micro droplet

T=265°C

T=305°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