Impact dynamics and heat transfer characteristics of liquid nitrogen drops on a sapphire prism

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Drops close to a hot solid surface can be prevented from making contact by the vapour generation in between them. This so-called Leidenfrost effect occurs at a minimal plate temperature which is referred to as the Leidenfrost temperature. In spray cooling, were one uses impacting drops to cool down the hot solid, this effect is very undesirable: the vapour layer forms an isolating layer and prevents effective heat transfer between the drop and the solid. We study this phenomenon by impacting a single liquid nitrogen drop on a smooth sapphire prism using high-speed frustrated total internal reflection imaging. In these cryogenic conditions, the prism behaves as a perfect thermal conductor, while its transparency enables us to study the contact behaviour during the impact and the spreading phase of the drop. By varying the prism temperature and impact velocity of the drops we obtain a phase diagram of the impact characteristics. Using the Stokes number for the vapour flow, we find good agreement with previous studies for non-cryogenic liquids. The phase diagram is then compared with a second type of experiment in which a stream of drops cools the prism over time. The results of the two different type of measurements agree well, from which we conclude that the cooling power of a drop is strongly related to the wetting behaviour of the impacting drops. Finally, by comparing the wetted area with the contact line length we show that heat transfer in contact and transition boiling is dominated by conduction rather than evaporation.

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1. Introduction

The interaction between drops and a wall is often used as an efficient way of heat transfer. In these so-called spray cooling systems, the latent heat of phase change is utilized to achieve temperature control in applications involving high heat flux densities, such as freezing food, cryotooling, power plants and cooling in reactors and process industries. The heat transfer coefficient for spray cooling however is a strong function of the wall superheat (the difference between the wall temperature $T_w$ and the saturation temperature $T_{sat}$ of the liquid) and depends on the dominant heat transfer mechanism. Three regimes are thus far identified: for low superheat the drops make good contact with the wall and bubbles nucleate at the liquid solid interface. While in this contact boiling regime the direct contact of the liquid with the solid allows for fast conduction, the largest contribution is the evaporation taking place at the contact lines of the numerous bubbles. The heat flux increases strongly until it reaches a maximum critical heat flux. This occurs at the Nukiyama temperature [1] and is followed by a rapid decrease of the heat transfer rate. This transition boiling regime ends at the Leidenfrost temperature [2–4], where a minimum in heat flux is found. It is the lowest temperature at which the drop is completely separated from the wall by a vapour film. The film acts as an insulating layer and the evaporation rate is greatly reduced. This regime is referred to as the Leidenfrost boiling or the film boiling regime.

The coupling between the hydrodynamics and the heat transfer makes the modelling of the heat transfer coefficient a challenging problem which has drawn a lot of attention [5–13]. Bridging of the gap between a single drop and a stream of drops is even a greater challenge: Not only does one have to deal with velocity and drop distribution, possible drop-drop interaction further complicate a proper description of the resulting heat transfer coefficient. Recently this was achieved for the film boiling regime by Breitenbach et al. [13]. Unifying models for the nucleate- and transition boiling regime however are still lacking [14]. Understanding of the various underlying heat transfer mechanisms is therefore crucial in achieving this.

Although many studies investigated the heat transfer coefficient previously, no visualisation of the wetting behaviour was possible as the target was made of a good thermal conducting
material, for which metals were used [15–17]. The use of metals eliminates the possibility of non-isothermal effects [18,19], however it hinders the possibility of studying the liquid–solid interaction directly. Recently, sapphire was used [11,20] as an impact target which can be considered isothermal only in the film boiling regime. Non-isothermal behaviour in the contact boiling and transition boiling regime is avoided in the current study by studying the impact of liquid nitrogen drops. Since for low temperatures sapphire exhibits excellent thermal conductivity the sapphire target remains isothermal during the interaction with the drop. We determine how the wetting behaviour and boiling regimes of single drops depend on impact velocity and plate temperature. Direct measurements of the wetted area and the contact length will allow us to find the dominant heat transfer mechanism to be conduction rather than evaporation. Next, we investigate the cooling rate of the sapphire target by a continuous stream of drops. The cooling rate of the impact target is an indirect measure of the cooling power of such a stream of drops. The two measurement types are then compared to learn more about the impact dynamics and determine the cooling effectiveness of drops during all the different types of boiling behaviour.

2. Experimental

Two setups are used in this study, which are presented in Fig. 1. The single drop experiments were performed in a cryo chamber, whose details are found in (a). Here, the impact velocity $U$ is varied as well as the temperature of the target $T_s$. We used two cameras to study the impact dynamics, which can be found in (b), whereas details on the drop generator are sketched in (c). The setup for the droplet stream measurements is presented in Figure (d). Let us now elaborate on the various experimental details, starting first with the cryo chamber. At the end of the section we discuss the droplet stream setup.

2.1. Single drop setup

2.1.1. Impact target

To study the wetting behaviour of individual nitrogen drops we vary the impact speed as well as vary the temperature of the impact target. The target is made of a smooth material and supported by a copper block to increase the total heat capacity. To observe the impacts from below we require the impact target to be transparent. We use a right-angle sapphire prism, whose side phases are 25 mm × 25 mm and have optically smooth surfaces. Sapphire was chosen as it has good thermal properties at room temperatures. At cryogenic temperatures it exceeds almost all materials in performance, having a thermal diffusivity of $10^{-3}$ m$^2$/s [21]. Whereas poor conducting materials suffer from local cooling effects, it was found that sapphire behaves isothermally at cryogenic temperatures since the thermal timescale is of the order of a second [18,19,22,23]. As a result, one can therefore accurately measure the prism temperature at a different position than the impact location as the diffusive response time is smaller than one second for $T_s < 150$ K. Another way of quantifying this is to evaluate the contact temperature [24] between the liquid and solid, which is less than three percent of the total plate superheat $\Delta T = T_s - T_{sat}$ for $T_s < 150$ K.

The temperature of the prism is measured using a thin film resistance sensor (Lake Shore Cernox) which was glued near the edge of the prism. Read-out was done by a Lake Shore 336 sampled at 10 Hz. The temperature of the prism was controlled indirectly by a large supporting copper block surrounding the sides of the prism. Two channels were made inside the block through which liquid nitrogen was pumped, while the lower part of the copper block was placed in a bath filled with liquid nitrogen. These two methods allowed us to cool the setup down to the saturation temperature of liquid nitrogen. To measure at different temperatures of the target we briefly interrupt the flow through the copper block. This results in an increase of the prism temperature. The drop is then generated at the desired prism temperature. The heating of the prism is too slow to change significantly during the residence time of the drop during impact.

The complete setup was enclosed by a cryogenic chamber (Fig. 1a). This allowed us to replace the air of the environment by nitrogen gas. This way frosting of the optics was prevented, as well as the roughness and poor thermal conduction of ice influencing the impact characteristics. Moreover, the oxygen in air can condense on the prism as well, forming a thin liquid layer, resulting in similar disturbances as ice formation. As a consequence, all electrical connections, gas- and liquid nitrogen connections and the drop generated were fed through gas-tight ports in the walls of the chamber. A large window was installed to allow the optical observation. The laser and the light source for the side view observation were placed outside the chamber. Two windows were used to illuminate and observe the experiment, aided by mirrors and beam expanders. Prior to the experiment, the setup was flushed by nitrogen gas to remove all contaminations which could deposit on the setup or the impacting drop.
2.1.2. Drop generation and velocity control

Nitrogen gas of high purity was used to create pure nitrogen drops by the process sketched in Fig. 1c. First, the gas was pre-cooled by submerging the gas tubing in a bath of liquid nitrogen. From the bath, the cold gas was led into the chamber through a small constriction. Since the gas was at an elevated pressure, the sudden drop in pressure created liquid drops as a result of constant enthalpy expansion. These droplets filled a small container from which single drops were created using the design by [25], which is shown in Fig. 1 as well. The method resulted in drops with a radius $R_0 = 1.1 \text{ mm}$.

Heat leaks from the surroundings result in the drops to be at $77.4 \text{ K}$, the saturation temperature of liquid nitrogen at one atmosphere. The gravitational acceleration was used to control the impact velocity by adjusting the height $h$ from which the drops were dispensed. Both the drop diameter and impact velocity were measured prior to impact for each measurement using the side view camera.

2.1.3. Imaging details

We study the dynamics and wetting by visualization of the phenomenon from the side and from below. Two high speed cameras (side view: Photron SA1.1 and bottom view: Photron SA-X2) were used, operating at a minimum frame rate of 20000 fps. For the bottom view, we employed the Frustrated Total Internal Reflection (FTIR) technique developed by [26–28] to study the wetting behaviour of the drop during impact.

For clarity we briefly describe the principle of FTIR-imaging now, as sketched in Fig. 1b. A laser is expanded by a set of lenses to illuminate the impact area from below. A transparent prism is therefore used as impact target for the drops. The laser light enters the prism through one of the sides, reflects on the long phase and exits the prism again. The light is captured by the camera, whose lens is focused on the impact plane to create a sharp image. The principle of FTIR is that the setup is aligned such that the laser hits the impact surface at an angle $\phi$ larger than the critical angle, which depends on the ratio of refractive indices of both air and the prism material. All light is reflected in the case of total internal reflection. Once a drop makes contact during impact however, the refractive index across the prism interface changes from that of air into that of the liquid. As a result, light propagates into the drop. Therefore, one can determine whether or not a drop makes contact with the impact target by the decrease in the captured intensity.

The FTIR-camera is focused onto the hypotenuse of the prism, the captured image is transformed by the difference in optical path length. Therefore, the image is transformed by post processing. The transformation is calibrated by imaging a sessile spherical water drop during the alignment of the optical system prior to measurement. FTIR imaging employed in studies of drop impact in room conditions use background division to compensate non-homogeneous lighting conditions. In our setup this method cannot be utilized: In room conditions the plate is heated, resulting in an upwards-moving plume of hot air. The cold prism in our setup however results in a downward moving plume, resulting in fast fluctuating disturbances of the laser light pattern, comparable to mirages. This renders the use of a single frame prior to impact as a background image obsolete as the fluctuations are too fast with...
respect to the measurement time scale. Therefore we can only use thresholding of the original images to discriminate between dry (black) and wetted (white) areas of the prism. The resulting binary image is then filtered to remove optical artefacts by removing objects smaller than 100 μm as a result of the aforementioned ‘mirages’. This threshold is to strict however for wall temperatures above 91 K as the wetted patches become small and disjointed. In these cases the filtering is altered manually. The wetted area is obtained by summing all detected patches, whereas the perimeter, i.e. the contact line length, is calculated by counting all pixels adjacent to black (background) ones. Results with and without the filtering differ 10%. The method treats enclosed bubbles on the surface as non-wetted areas, thus decreasing the wetted area and increasing the contact line length.

2.2. Continuous stream setup

Comparison with the cooling rate of a droplet stream was achieved by creating a liquid nitrogen jet. The jet will break up into small drops which impact on the target, for which we used the same sapphire prism as in the single drop experiments. The prism was suspended inside an open-top metal box by a net. The sides and bottom of the box were covered by Multi Layer Insulation to shield the prism from radiation. The temperature of the prism during measurement was measured by a Cernox probe and recorded by a Lakeshore controller 336. The droplet stream was created from a vacuum flask, which was filled with liquid nitrogen prior to measurement, see Fig. 1. Two holes were made in the top of the flask. Microfluidic tubing with an inner diameter of 0.76 mm was installed in the first hole, which was long enough to reach to the bottom of the flask, whereas the second hole was connected to a nitrogen-gas supply. By means of a pressure regulator we could control the pressure in the flask. The overpressure then pushes out the liquid nitrogen through the tubing in the form of a jet. The flask emptied typically after 500 s. The velocity of the jet was 1 m/s, resulting in a breakup frequency of 148 Hz and drop radius of 1.89 times the jet radius [29]. The flask was slightly inclined such that the jet had a parabolic trajectory against gravity. The velocity of the drops prior to impact was controlled by altering the vertical position of the target relative to the maximum height of the droplet stream. Based on the analysis from Breitenbach et al. [13] we find the stream to be sparse, i.e. the drops rarely interact with each other as a result of their temporal spacing. Moreover, fluctuation in the lab environment make the drops to be scattered over a small area of the impact target instead of a single point. The stream can thus be treated as a series of individual impacts. Finally, let us stress once more that the good thermal properties of the sapphire impact target for cryogenic temperatures ensures an isothermal cooling process. It also enables accurate remote measurement of the temperature without influencing the impact dynamics.

3. Results

3.1. Single drop impact

Using the setup described earlier the impact behaviour of liquid nitrogen drops was studied, varying the impact velocity $U$ from 0.2 m/s to 1.6 m/s and the prism temperature $T_p$ from 80 K to 110 K. A series of snapshots for $U = 1.3$ m/s is shown in Fig. 2, where $T$ is varied. Each series shows the side view observation with the post-processed bottom view recordings, where contact between the prism and the drop is displayed in white. For $T_p = 81.0$ K the drop wets the surface completely, except for some small bubbles. A good correspondence can be found between the spreading radius as observed by the sideview and the radius of the wetted area. This behaviour is referred to as contact boiling.

When the prism temperature is increased, this correspondence is lost and the wetting radius is reduced as a result of the strong evaporation at the periphery of the drop. The periphery is also less smooth, which is clearly demonstrated for the measurement at $T_p = 88.7$ K. Cases where the wetted area is smaller than the spreading radius are referred to as transition boiling. With increasing temperature the wetted area decreases further (c) until the contact is only established for the very early times, for some cases only during a single frame of the recording. The flow-focusing occurring inside the drop results in a local pressure peak, forcing the drop into contact with the plate [11,30,31]. The resulting ring structure is visible in the center of the measurements of $T_p = 92.1$ K. Since the drops spread faster [8,32], and are not in full contact with the prism, the fragmentation behaviour is also altered. Splashing is observed at lower impact velocities than in the case of contact boiling. This is in agreement with studies with ‘common’ non-cryogenic liquids such as water [10,33] and ethanol [9].

The last series shows an impact where no contact is observed: wetting of the prism is prevented by a vapour layer, which is generated by the strong evaporation of the drop. The drop is now in the Leidenfrost state. Although the side view observations are similar compared to the impacts at lower temperatures, the FTIR imaging provides a clear distinction between transition and Leidenfrost boiling. By varying the impact velocity and plate temperature, the boiling behaviour of each impact is studied. The results are presented in the phase diagram displayed in Fig. 3.

We observe that both the temperature $T_{lb}$ for which transition boiling is observed is almost independent of the impact velocity. Previous studies found this trend for the boundary between contact and transition boiling as well. We find this change in boiling behaviour to occur at $T_p \approx 87$ K. It was suggested by [11] that this temperature correlates with the static Leidenfrost temperature. Indeed, comparison of our data with that of Keshock and Bell [34], reveals that this also holds for the present case of liquid nitrogen. The boundary between the transition and Leidenfrost boiling, i.e. the dynamic Leidenfrost temperature $T_{lb}$, was found to have a very weak dependency on the impact velocity, saturating for $U > 0.6$ m/s. Good agreement can be found when introducing the capillary number $Ca = \eta \gamma / \rho g R_d$ and the Stokes number $St = \rho U / \eta g$. Here $\eta$ is the vapour viscosity, $\gamma$ the drop interfacial tension, $R_d$ the drop radius and $\rho$ the density. According to [35,36] we find that our impacts are in inertial regime, having a cross-over with capillary effects when $St^{2/3} \sim Ca^{1/2}$, which yields in the present case $U \approx m/s$. The relative small velocity range of the current study is compensated by the low dynamic viscosity of cold nitrogen gas. This results in a similar range of $St = 3 \times 10^4$ to $28 \times 10^4$ as that of non-cryogenic studies [11], where the $T_{lb}$ was found to saturate with increasing velocity as well. It is interesting to observe that the transition boiling temperature range $T_1 - T_2$ is much smaller in the case of liquid nitrogen compared to the non-cryogenic fluids, see Table 1. When these values are compared on a reduced coordinate, $\Theta_{lb} = (T_1 - T_{lb})/T_e$ they collapse to value close to 0.10.

Let us now focus on the wetting behaviour of the drops. The wetted area $A_{wetted}(t)$ and the contact line length $L_{cp}(t)$ is extracted from the FTIR-images various prism temperature and shown over time in Fig. 4 for m/s. To compare different impact velocities, the time is rescaled by the impact timescale $2R_0/U$ [39], whereas the length scales are rescaled by the initial drop radius $R_0$.

As described previously, the drops are in the contact boiling regime for low superheat. Consequently, no large vapour patches are present, see Fig. 2. The wetted area increases linearly with time,
see Fig. 4a, since the wetted radius scales with $r^{1/2}$ [30] for early times. With increasing prism temperature the wetted area diminishes, until no contact is found in the Leidenfrost case. The reduction of the wetted area results in the decline in heat transfer as the vapour insulates the drop. Similar effects are also observed in pool boiling, where a temperature difference is found between the maximum and minimum heat flux temperature [22,40].

Fig. 2. Four sequences for nitrogen drops impacting a sapphire prism at $T_s = (a) 81.0$, (b) 88.7, (c) 92.1, and 106.0 K. The top image of each sequence shows the side view, whereas the bottom reveals the wetted area in white as obtained by FTIR-imaging. The impact velocity $U$ is 1.3 m/s for all cases.
Our measurements also allow for the determination of the dominant heat transfer mechanism in the system. Firstly, the direct contact between the hot solid and the drop allows for strong conductive cooling, which scales as [41]

$$Q_{\text{cond}}(t) \sim k_l \Delta T_{\text{wetted}}(t)/\sqrt{\alpha_l t}.$$  (1)

Here, $\Delta T = T_c - T_{\text{sat}}$ is the wall superheat above the liquid saturation temperature. The thermal boundary layer is assumed to grow as $\sqrt{\alpha_l t}$, with $\alpha_l$ being the thermal diffusivity of the liquid. $k_l$ is the liquid thermal conductivity. The liquid is superheated above saturation since no free interface exists for phase change [42]. The second heat transfer mechanism is due to evaporation at the contact line between solid, liquid and vapour:

$$Q_{\text{cl}}(t) = \frac{1}{2} A_{\text{wetted}}(t).$$  (2)

The term $Q_{\text{cl}}$ is here the integrated heat flux near the contact line, as defined by Herbert et al. [43]. The similarities in thermophysical properties between liquid nitrogen and FC-72 (see Table 2) allows us to utilize their results and model this as a function of wall superheat $\Delta T$. All results of their Fig. 6 can roughly be approximated by $Q_{\text{cl}} \approx 0.2 \text{ W/(m K)}/\Delta T$. This order of magnitude is in agreement with single bubble measurements in pool boiling [44], when assuming that all heat is transferred by contact line evaporation. It should be noted we adopt the results of Herbert et al. to the transition boiling case, whereas their results are based on the contact boiling regime. Future studies might yield different values for $Q_{\text{cl}}$ for transition boiling situations. This is however beyond the scope of the current study. The ratio between the conductive and evaporative heat transfer can now be estimated as:

$$\frac{Q_{\text{cond}}}{Q_{\text{cl}}} \approx \frac{k_l A_{\text{wetted}}}{2\sqrt{\alpha_l L_{\text{cl}}}}.$$  (3)

The ratio $A_{\text{wetted}}/L_{\text{cl}}$ can be interpreted as the inverse of a contact line density and is presented in dimensionless form in Fig. 4b, where the area is normalized by $R_0^2$ and the contact line length by $R_0$. The value is a measure of how much liquid contacts the plate per unit length of contact line. Data is shown for a contact boiling case and four transition boiling cases. During contact boiling, the ratio $A_{\text{wetted}}/(R_0 L_{\text{cl}})$ follows the square root behaviour since $R \sim t^{1/2}$ [30] and $A \sim \pi R^2$. The transition boiling case shows a higher densities of contact lines, which also increases over time. Fig. 5 presents Eq. (3) during the impact. It should be noted that Eq. (3) should be treated as a scaling argument, rather than quantitative measurements. Nonetheless, the data reveals clearly that for all temperatures the conductive contribution exceeds the evaporative part, which might be counter intuitive. Since the evaporative part scales with the latent heat, this behaviour is likely to be less pronounced for polar liquids, which have high latent heats compared to liquid nitrogen. Data for $T_c = 89.0 \text{ K}$ differs from 89.3 K as a result of surface contamination. The resulting increase of air entrapment, leading to micro bubbles [46], act as nucleation sites for evaporation and hence increase $Q_{\text{cl}}$. Numerical simulations from Healy et al. [47], and Francois and Shyy [48] are in agreement with the present results: Here, the conductive part is of the same order as the heat transfer near the contact line. The ratio between area and contact line length however results in a dominant role for conduction. Herbert et al. [43] show a direct numerical evaluation of Eq. (3), finding a maximum of the ratio to be 7. Global heat transfer rates are more available in the literature. Estimating $q^* \sim k_l \Delta T/\sqrt{\alpha_l t}$ yields values of order $1 \times 10^6 \text{ W/m}^2$, for $t \approx 10^{-3} \text{ s}$, in agreement with the literature [22,41,43,47].

Eq. (3) estimates the thermal boundary layer thickness very conservatively. During the spreading of the drop, newly formed wetted patches are treated as if their boundary layer started formed at $t = 0$. It is also this boundary layer which differentiates the dominant heat transfer mechanism during drop impact and

### Table 1
Comparison of the boiling regimes for various liquids in the high Stokes number limit. $\theta_{\text{bh}} = (T_c - T_{\text{sat}})/T_c$. Critical heat flux temperature is taken for $T_{\text{bh}}$ in the case of studies without bottom view.

<table>
<thead>
<tr>
<th>Ref</th>
<th>Temperature</th>
<th>Water</th>
<th>Water</th>
<th>Ethanol</th>
<th>FC84</th>
<th>Acetone</th>
<th>Heptane</th>
<th>Heptane</th>
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<td>$T_{\text{sat}}$ [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>$T_{\text{bi}}$ [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>
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<tr>
<td>$T_c$ [K]</td>
<td>103</td>
<td>573</td>
<td>493</td>
<td>493</td>
<td>473</td>
<td>473</td>
<td>473</td>
<td>483</td>
</tr>
<tr>
<td>$T_{\text{bh}}$ [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>$\theta_{\text{bh}}$ [-]</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>
</tr>
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</table>
3.2. Droplet stream

With the characterization of impact behaviour of single-drops done, it is interesting to study the heat transfer characteristics. A stream of drops is used to cool down the impact target, which is the prism used previously. Details on the stream can be found in the experimental Section 2. While the stream cools the prism, the temperature is recorded for four different impact velocities \( U = 0.8, 1.1, 2.0, 2.8 \) over time and presented in Fig. 6a. The different measurements are shifted such that the prism reaches the saturation temperature of liquid nitrogen (77.4 K) at the same time for all measurements. For all of the cases, the nitrogen jet was created under the same conditions, i.e. the mass flux, drop size and impact frequency being the same. Fig. 6b is a magnification of the data near \( T_s = T_{\text{sat}} \). It is clearly visible that the cooling is velocity independent for \( T_s < 90 \) K: all curves collapse. This observation is in good agreement with the velocity independent regime boundary between contact and transition shown in Fig. 3. Whenever contact boiling is observed, the drop wets the prism completely and the majority of the drop contributes to the cooling, whereas in the transition boiling regime the majority of the drops simply bounce off the prism after a brief moment of contact (or even no contact in the case of Leidenfrost boiling). The second measurement technique thus allows for an indirect assessment of when the contact boiling regime begins.

Focusing on the cooling rate \( dT_s/dt \) a velocity dependency is found while the prism is at \( T_s > 120 \) K. Fitting a linear trend to our data yields the cooling rates presented in Fig. 6c, which themselves follow a linear dependency on the velocity in the range studied. In the limit of \( U = 0 \) a finite cooling rate is still found, corresponding to the evaporation of static Leidenfrost drops. It is interesting to relate these results to the heat transfer coefficient \( H \): Using a simple heat balance for our system

\[
 C \frac{dT_s}{dt} = B(H(T_s - T_{\text{sat}})),
\]

where \( B \) is a constant depending on the hydrodynamical parameters of the stream and \( C = mc_p \), with \( m \) the mass of the prism. \( C_p \) can be fitted in the temperature range of \( T_s = 120 \) till 300 K by \( 0.37 - 0.15 (\text{J/mol/K}) \) [49]. The ratio \( C_p(T_s - T_{\text{sat}}) \approx 0.4 \text{J/mol/K}^2 \), from which

\[
 H = \frac{m(0.37T_s - 0.15)}{B(T_s - T_{\text{sat}})} \approx \frac{dT_s}{dt} \frac{dT_s}{dr},
\]

is obtained for large \( T_s \). The linear behaviour of \( H \) with velocity can be understood adopting the model of Breitenbach [13], which models the heat transfer coefficient of a spray of liquid in the film boiling regime. In their model, the spreading of the drop is assumed as \( \sqrt{t} \) until \( t \) reaches the impact timescale \( \tau_{\text{imp}} = 2k_h/U \). A Weber dependency in the spreading [8,32,50] was only introduced for the interaction between drops, not for the spreading of a single drop. For large \( W \) however, the inertia-capillary time scale should be used for the residence time:

\[
 \tau_{\text{cap}} \approx \sqrt{\frac{\rho R^3}{\gamma}}.
\]

Instead of the impact timescale \( \tau_{\text{imp}} [50,51] \). One then recovers \( H \approx U \) instead of \( H \approx U^{-1/2} \), which is in good agreement with our data and literature [33].

4. Conclusion

We studied the impact of single drops as well as a droplet stream of liquid nitrogen on a sapphire smooth target. The transparency and excellent thermal properties of (low temperature) sapphire allowed for total internal reflection imaging as well as isothermal behaviour, even in the contact boiling regime. By varying the drop impact velocity and the target temperature we mapped the boiling behaviour in a phase diagram. Combining single drop measurements with continuous droplet stream we were able to correlate the cooling rate with the wetting behaviour of a single drop. Good agreement was found between the phase diagram and the various cooling curves. Similar to non-cryogenic studies, we found the end of the contact boiling regime to correlate with the static Leidenfrost temperature. The Stokes number for the vapour flow clarifies the rapid increase in dynamic Leidenfrost temperature at low velocities, followed by a saturation for \( St \approx 10^5 \). This behaviour is in agreement with non-cryogenic liquids found in literature. Our images also allow to compare the wetted area with the contact line length in the contact and transition

| Substance | \( h_{\text{eff}} \) [W/m²K] | \( 
\varepsilon \) | \( h_{\text{lat}} \) [J/kg] | \( \frac{1}{\tau_{\text{imp}}} \) [s] |
<table>
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<tbody>
<tr>
<td>N₂</td>
<td>2.0 \times 10^5</td>
<td>476</td>
<td>1.6 \times 10^8</td>
<td>1.5 \times 10^{-15}</td>
</tr>
<tr>
<td>FC-72</td>
<td>0.9 \times 10^5</td>
<td>304</td>
<td>1.4 \times 10^8</td>
<td>1.5 \times 10^{-15}</td>
</tr>
</tbody>
</table>

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Fig. 5. Eq. (3) for various \( T_s \), whereas \( U = 0.6 \) m/s. Data correspond to Fig. 4.

that in pool boiling. In the latter case, the thermal boundary layers are much thicker, hence making evaporation the dominant contribution to the global heat transfer rate.

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Fig. 6. A stream of liquid nitrogen lowers the temperature of the prism over time (a), where (b) shows the behaviour near \( T_s = T_{\text{sat}} \). The colours of the shaded areas correspond with the three different boiling behaviours, as presented in the phase diagram Fig. 3. Four different impact velocities \( U \) result in different cooling rates (c) in the temperature range \( T_s > 100 \) K (see the black lines in (a)), exhibiting a linear dependency in \( U \). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
boiling regime. These measurements allow us to compare the conductive heat transfer with the evaporation at the contact line. We conclude conduction to be the dominant mechanism, a consequence of the thin thermal boundary layer in the drop. Next, the cooling of the target was studied using the droplet stream. A roughly linear scaling in velocity for the cooling power as well as heat transfer coefficient was found. We have shown that the change of cooling power above a certain target temperature relates to the type of boiling behaviour as observed from our bottom view. This has great implications for understanding of the different heat transport mechanisms in spray cooling. Evaporation is strongly promoted at contact lines, and in those boiling regimes we found the cooling to be strongest.

Declarations of Competing Interest

None.

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