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

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ABSTRACT

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.

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_s 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

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Nomenclature

α_l	drop thermal diffusivity [m ^{2}/s]
ΔT	wall superheat $T_s - T_{sat}$ [K]
$\dot{Q}_{cond}$	rate of conductive heat transfer [W]
$\dot{Q}_{cond}$	rate of evaporative heat transfer [W]
η_v	vapour viscosity [Pa s]
γ	surface tension [N/m]
ϕ	angle of incidence for FTIR-illumination
ρ	liquid density [kg/m ^{3}]
τ_{imp}	impact time scale [s]
Θ_{tb}	non-dimensional temperature range of transition boiling regime
A_{wetted}	drop wetted area [m ^{2}]
C	specific heat of target ($= mc_p(T)$) [J/K]
Ca	capillary number ($= \eta_v U/\gamma$)
H	heat transfer rate [W/(sK)]
h	impact height
k_l	liquid thermal conductivity [W/m/K]
L_{cl}	contact line length [m]
R_0	initial drop radius [m]
R_s	drop spreading radius [m]
R_w	drop wetting radius [m]
St	stokes number ($= \rho U R_0/\eta_v$)
t	time after impact (single drop) or time before $T_s = T_{sat}$ (stream) [s]
T_L	dynamic Leidenfrost temperature [K]
T_s	temperature of target [K]
T_{sat}	saturation temperature [K]
T_{tb}	minimum temperature for transition boiling [K]
U	impact velocity [m/s]
We	Weber number ($= \rho U^2 R_0/\gamma$)

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.

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