DROP IMPACT MORPHOLOGY ON HEATED SURFACES

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ABSTRACT
The impact morphology of water drops on a polished aluminium surface has been studied experimentally by high-speed imaging, for surface temperatures between 50°C and 400°C, and Weber numbers up to 160. Five impact regimes are defined based on the final outcome of the impact: three independent regimes (secondary atomisation, rebound, and splashing), and two mixed regimes (rebound with secondary atomisation and splashing with secondary atomisation). Impact regimes are displayed on a quantitative two-dimensional map, having the surface temperature and the impact Weber number at ambient conditions as coordinates. Some characteristics of the transition boundaries between impact regimes are discussed.

INTRODUCTION

The impact of liquid droplets on heated surfaces is a complex phenomenon, characterised by a close interplay of hydrodynamics with different heat transfer modes, under large spatial and temporal gradients of the state variables (see, e.g., [1]). Despite its complexity, and the fundamental scientific challenges it gives the research community, drop impact on heated surfaces is commonplace in several practical applications. These include spray cooling, painting, inkjet printing for advanced manufacturing processes, and nuclear reactor safety

From a qualitative standpoint, this phenomenon consists of three stages: approach (between drop generation and impact), spreading (between impact and maximum spreading), and final outcome (after maximum spreading).

During the approach to a heated surface, the drop falls in counter-flow to a rising plume of hot air. This initiates to initiates to heat the liquid, and slightly reduces the impact velocity with respect to the theoretical free-fall velocity; moreover, the drop is exposed to radiation from the heated surface, which is not negligible at higher temperatures.

After impact, the drop spreads on the heated surface in a short lapse of time (~5 ms), increasing the area exposed to heat transfer. This induces a heat transfer regime that can be related to the well-known boiling curve. In particular, one can observe convection for surface temperatures below the boiling point of the liquid, nucleate boiling, film boiling, where the drops is separated from the surface by a vapour cushion, and transitional boiling, where the said vapour cushion is unstable and the liquid may locally get into contact with the surface.

After maximum spreading, different final outcomes are possible, depending on the impact velocity, the fluid and surface properties, and the surface temperature. If perturbations on the free surface of the liquid are too large, then the drop will break down into smaller droplets (splashing). Otherwise, it will recoil in order to minimise the surface energy, and eventually bounce off the surface if there is sufficient kinetic energy at the end of the recoil.

Early studies of this phenomenon focused on the heat transfer characteristics [2], [3], and less attention was paid to drop impact morphology due to the limitations of stroboscopic imaging [4]. Later on, the development of high-speed imaging has allowed researchers to visualise and analyse more quantitatively the various impact regimes [5]-[7]. However, a comprehensive and detailed study of drop impact morphology on heated surfaces using 3-D imaging was published only very recently [9]. In particular, this work presents a fine analysis of the physical mechanisms behind different impact outcomes, sometimes highlighting differences that can hardly be noticeable from the mere analysis of the final outcomes.

The first attempt to construct a global mapping of drop impact regimes on heated surfaces was proposed by Bernardin and co-workers [6]. This work, however, focuses on the temporal evolution of the drop morphology rather than on the final outcome, which is of greater importance in practical applications. Rein [1] proposed a qualitative impact regime map using the surface temperature and the impact Weber number as coordinates. However, transition boundaries between different impact regimes are not defined quantitatively.

The present work aims at proposing a classification of drop impact regimes on a heated surface, which is based on physical principles, but at the same time can be useful in practical applications. These regimes are then plotted on a two-dimensional map, where transition boundaries are defined quantitatively.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental setup is schematically described in Figure 1. Drops of de-ionised water (Barnstead Easypure II) were released from a blunt hypodermic needle (gauge 21, i.d. 0.495 mm) and impacted on a polished aluminium surface electrically heated and kept at constant temperature by a PID controller.

Drop weight measurements made with a precision balance (Mettler Toledo MT100) allowed calculation of the drop diameter at equilibrium, $D_0 = \sqrt[3]{6m/\pi\rho}$: the average value, calculated over 50 samples, was 3.09 ± 0.1 mm. The drop equilibrium radius, $D_0/2$, was therefore smaller than the capillary length, $a = \sqrt{\sigma/\rho g}$ (2.48 mm), which is indicative of the competition between surface forces and gravity: thus, surface forces prevail ensuring that the equilibrium shape of drops is spherical.

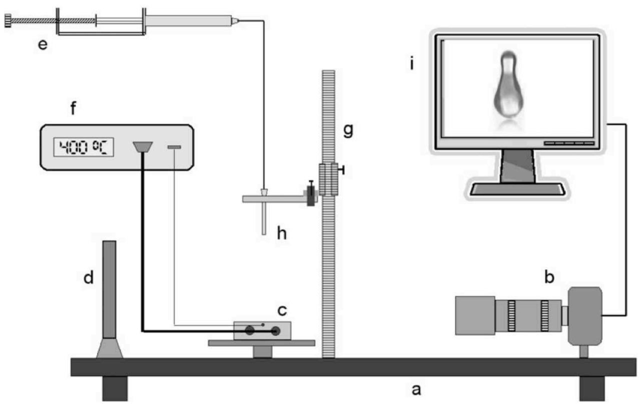

Figure 1: Schematic of the experimental setup: (a) optical breadboard (b) high-speed camera (c) heated aluminium block (d) LED backlight (e) drop dispensing system (f) temperature controller (g) height gauge (h) needle (i) computer.

Adjusting the position of the dispensing needle with a digital height gauge allowed changing the impact velocity hence the impact Weber number, $We = \rho D_0 u^2 / \sigma$, which expresses the competition between kinetic energy and surface energy. For falling heights smaller than 15 cm, the impact velocity is almost identical to the theoretical free fall velocity, $u = \sqrt{2g\left(H - D_0\right)}$ [11], so that the Weber number can be calculated as:

$$We = \frac{\rho D_0 u^2}{\sigma} = \frac{2\rho g D_0 \left(H - D_0\right)}{\sigma} \tag{1}$$

In the present work, the impact Weber number ranged between 7 and 160.

The impacts of single drops were recorded using a high-speed CMOS camera (Mikrotron MC1310) at the rate of 1000 frames per second. The camera was horizontally aligned with the impact surface in order to measure the bouncing height of the drop with precision. Back-to-front illumination was provided by a LED light source equipped with light diffuser (ThorLabs).

For each set of experimental parameters (i.e., surface temperature and Weber number), the impact experiment was repeated five times for the sake of statistical analysis.

Figure 2: Typical outcome of drop impact on a surface at a temperature below the boiling point of the liquid (T = 100°C, We = 100): the drop is deposited on the surface and convection is the main heat transfer mode.

RESULTS

Morphology of impact regimes

For temperatures of the impact surface below the boiling point of water, the only active heat transfer mode is convection. This does not significantly affect the impact morphology as compared with homo-thermal impact (Figure 2). Thus, the impact morphology depends only on the fluid and surface properties, and on the impact velocity.

When the surface temperature is above the boiling point, vapour bubbles created on the hot surface rise by buoyancy and burst on the free surface of the drop, scattering a great number of satellite droplets (Figure 3).

The intensity of secondary atomisation may vary depending on the surface temperature or the impact Weber number (compare, e.g., the two cases in Figure 3). The size distribution of secondary droplets is not uniform, but bi-modal, with smaller droplets created by bubbles bursting on the liquid free surface with a bag-breakup mechanism [10], and bigger droplets created by free-surface instabilities. Secondary atomisation depends much on the surface properties, and in particular on its thermal effusivity [11].

For high temperatures (T > 350°C in the case of water on polished aluminium), two outcomes are possible: drop rebound (Figure 4), for low Weber numbers (We < 100), and drop splashing (Figure 5) for higher Weber numbers.

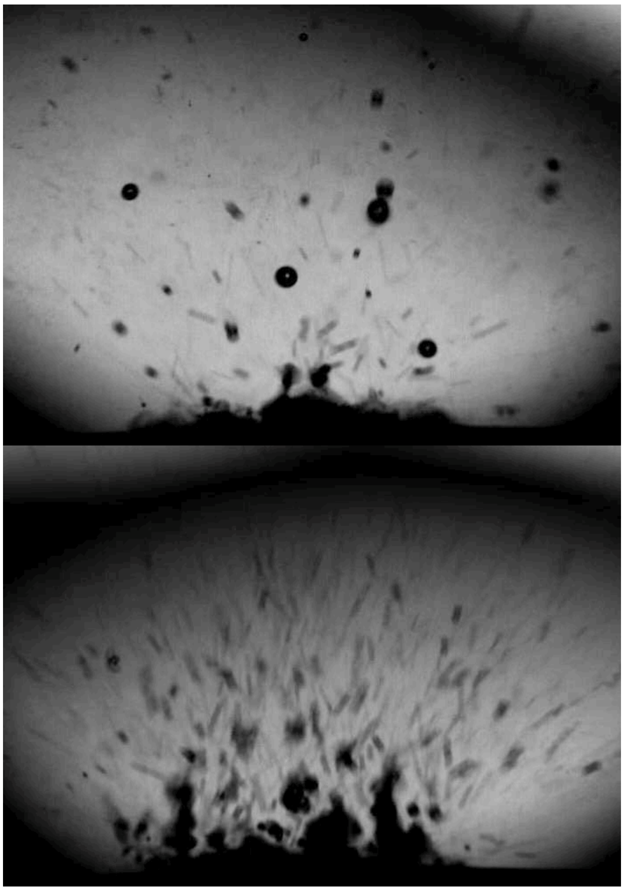

Figure 3: Typical outcome of drop impact on a surface at a temperature above the boiling point of the liquid (top: T = 150°C, We = 40; bottom: T = 150°C, We = 100): the drop ejects minuscule satellite droplets (secondary atomisation).

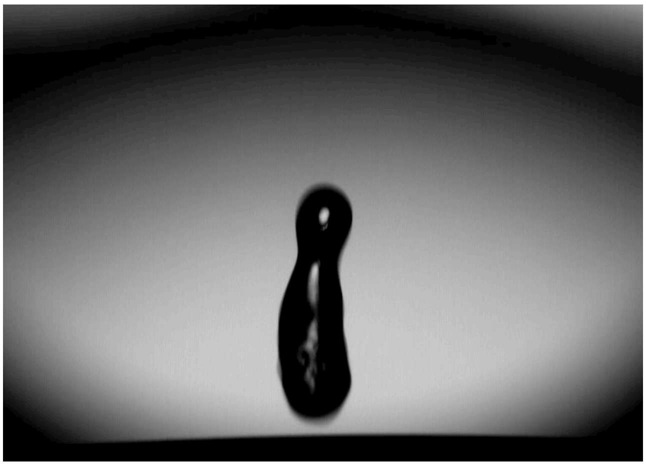

Figure 4: Typical outcome of drop impact on a surface at a temperature above the dynamic Leidenfrost point and low Weber numbers (T = 400°C, We = 40): the drop bounces on the surface without secondary atomisation.

Drop rebound occurs because at high temperatures (i.e., well above the Leidenfrost point [3],[12]) a vapour film forms between the liquid and the surface immediately upon impact. This vapour film acts as a lubricant layer, reducing energy dissipation during drop spreading and recoil. Therefore at the end of retraction there is still some kinetic energy available for rebound. This regime can be associated to the film boiling heat transfer mode, characterised by a stable vapour layer, which prevents any contact between the liquid and the surface.

For temperatures below 350 °C, one can observe two additional mixed regimes: rebound with secondary atomisation (Figure 6), and splashing with secondary atomisation (Figure 7).

These regimes are characterised by an unstable vapour film between the drop and the impact surface. This allows local contact between the liquid and the hot surface, where vapour bubbles can grow and generate secondary atomisation as they burst on the free surface of the drop. Unlike secondary atomisation shown in Figure 3, which occurs with the nucleate boiling heat transfer regime, these two regimes occur with transition boiling.

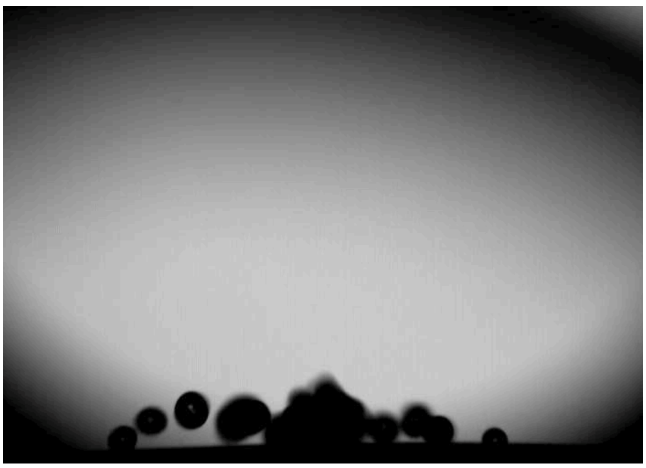

Figure 5: Typical outcome of drop impact on a surface at a temperature above the dynamic Leidenfrost point and High Weber number (T = 400°C, We = 100): the drop breaks down into smaller droplets (splashing).

Figure 6: Typical outcome of drop impact on a surface at a temperature below the dynamic Leidenfrost point and low Weber numbers (T = 250°C, We = 40): the drop bounces and simultaneously scatters secondary droplets.

Impact regime map

The occurrence of impact regimes described in the previous section can be visualised graphically on a two-dimensional map, which is shown in Figure 8, and whose coordinates are temperature and the reference Weber number at ambient conditions (i.e., with the fluid properties at ambient temperature).

Whilst the map is valid specifically for water drops on polished aluminium, it can also be representative of other systems, at least qualitatively.

The boundary between the *rebound* and *rebound with secondary atomisation* regimes defines the so-called dynamic Leidenfrost temperature, i.e. the minimum temperature to observe dry rebound, without secondary atomisation. Yao and Cai [5] proposed the following empirical correlation for the dynamic Leidenfrost temperature as a function of the Weber number:

$$T_{LD} = T_S + 135.6We^{0.09} \tag{2}$$

where T_S is the saturation temperature of water.

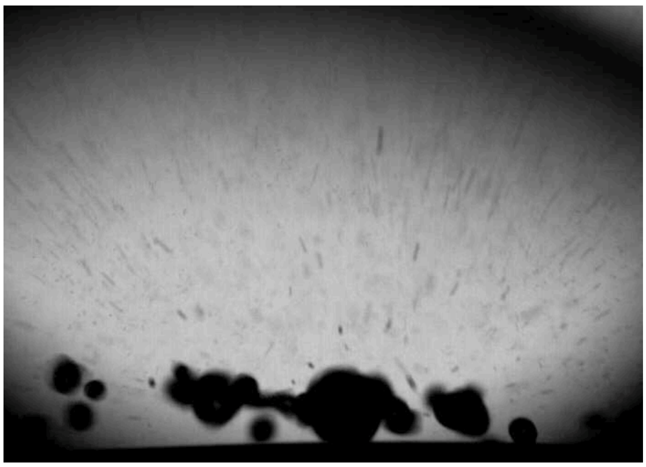

Figure 7: Typical outcome of drop impact on a surface at a temperature below the dynamic Leidenfrost point and high Weber numbers (T = 250°C, We = 100): the drop splashes and simultaneously scatters secondary droplets.

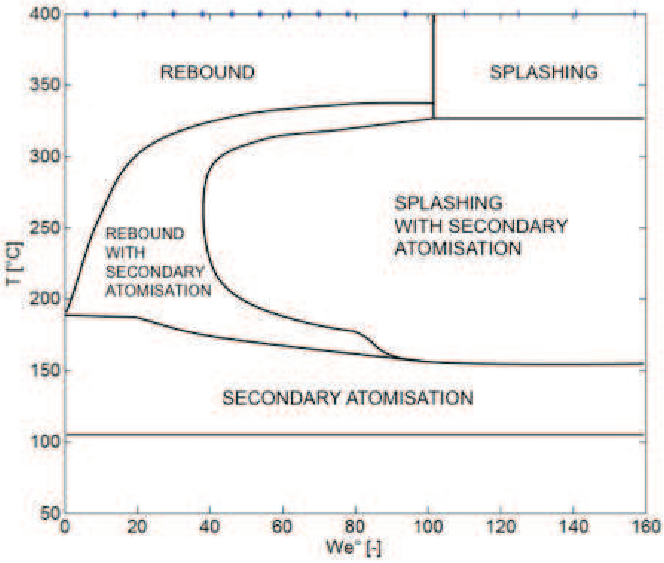

Figure 8: Impact regime map for water droplets (D ≈ 3mm) impacting on a heated, polished aluminium surface,

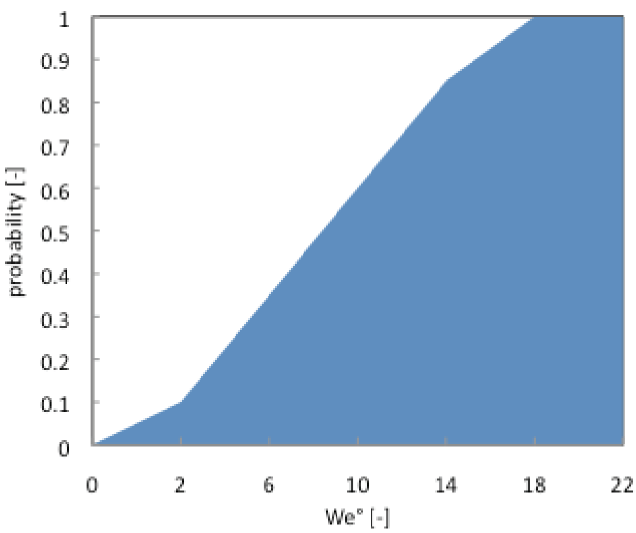

Figure 9: Probability of observing secondary atomisation during drop impact on a surface at 250°C, as a function of the Weber number.

However, Eq. (2) cannot predict the Leidenfrost temperature for a drop gently deposited on a hot surface (We → 0), which is significantly higher than T_S [12], therefore this transition is better characterised by correlations in the form:

$$T_{LD} = T_L + AWe^b \tag{3}$$

where T_L is the Leidenfrost temperature, and A and b empirical constants.

Another phenomenon that receives much attention is the onset of splashing, which is usually characterised in terms of the K dimensionless number [13][14].

$$K = WeOh^{-2/5} \tag{4}$$

where Oh is the Ohnesorge number:

$$Oh = \frac{\eta}{\sqrt{\sigma\rho D_0}} \tag{5}$$

It was found that splashing occurs at a constant value of the K number, for drops impacting on both dry and wetted surfaces [15]. Empirical correlations were also proposed to take into account the effects of surface roughness and of the relative liquid layer thickness [16].

Figure 8 shows that the splashing criterion based on the K number (K = const.) applies to impacts on heated surfaces in the Leidenfrost regime (i.e., with surface temperature above the dynamic Leidenfrost point), as well as to impacts on dry and wetted surfaces. Indeed, for assigned fluid properties and drop diameter, the condition K = const. reduces to We = const. This is no longer true in for the transition between mixed regimes (i.e., in the presence of secondary atomisation).

It is important to remark that the transition boundaries reported in Figure 8 are plotted as a function of the Weber number at ambient conditions, We°, therefore they may not reflect entirely the physical mechanisms of transitions.

In fact, the fluid properties, hence the dimensionless groups introduced above, change with the fluid temperature. For example, when the fluid temperature changes from 20°C to 99°C, viscosity reduces from 1 mPa·s to 0.28 mPa·s, and surface tension reduces from 72 mN/m to 58 mN/m; this causes the Weber number to increase by 20%, the Ohnesorge number to reduce by 70%, and the K number to increase by 90%.

Another important feature of these transitions is their probabilistic nature: if one repeats an impact experiment several times with experimental conditions (i.e., surface temperature and Weber number) close to a transition boundary between two different impact regimes on the map displayed in Figure 8, both outcomes will be observed.

For example, if one considers the transition between the "rebound" regime and the "rebound with secondary atomisation" regime, at a temperature of 250°C, one finds that the probability of observing secondary atomisation has the trend shown in Figure 9, i.e. the probability can be non-zero even before the transition boundary. Taking the derivative with respect to the Weber number of this probability function returns the probability density function of the boundary location, which therefore is not a line but is "smoothed" over a certain area.

CONCLUSION

Extensive drop impact experiments on a heated surface, covering a range of surface temperatures and Weber numbers, led to propose a classification of impact regimes based on the final outcome rather than on the details of the drop morphology during impact.

Such impact regimes were displayed on a quantitative two-dimensional map, which can be used to predict the drop impact outcome for assigned impact Weber number and surface temperature.

The transition boundary between the rebound and rebound with secondary atomisation regimes, as well as that between rebound and splashing, are consistent with results reported in the literature.

NOMENCLATURE

Symbol	Quantity	SI Unit
a	Capillary length	m
D_0	Drop diameter	m
g	Gravity	ms^{-2}
H	Falling height	m
K	K-number	-
L	Length, distance	m
m	Mass	kg
Oh	Ohnesorge number	-
T	Temperature	K
u	Velocity	ms^{-1}
We	Weber number	-

Greek:

η	Viscosity	Pa·s
ρ	Density	kgm^{-3}
σ	Surface tension	Nm^{-1}

Subscripts and superscripts

L	Leidenfrost
LD	Leidenfrost, dynamic
S	Saturation conditions
°	Ambient conditions

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