



# An impact regime map for water drops impacting on heated surfaces



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## ABSTRACT

The impact morphology of millimetric water drops on a polished aluminium surface has been studied experimentally by high-speed imaging, for surface temperatures between 50 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.

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## 1. 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 [1]. However, drop impact on heated surfaces is also commonplace in several practical applications: these include spray cooling, painting, inkjet printing for advanced manufacturing processes, and nuclear reactor safety.

Early studies of these phenomena 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 [5–8]. Recently, a careful study of drop impact morphology on heated surfaces using 3-D imaging [9] presented a very detailed analysis of the physical mechanisms behind different impact outcomes.

From a qualitative standpoint, drop impact on a heated surface can be described as a sequence 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 counterflow to a rising plume of hot air. This begins 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 high temperatures.

After impact, the drop spreads on the heated surface in a short lapse of time (typically a few milliseconds in case of drops of millimetric size), 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 heat transfer for surface temperatures below the boiling point of the liquid; nucleate boiling for surface temperatures just above the boiling point; film boiling, observed above the critical heat flux (CHF), where the drop is separated from the surface by a vapour layer; transitional boiling, where the said vapour layer is unstable and the liquid may locally get into contact with the surface. However, the association between heat transfer and impact regimes is not always clear [7].

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 (breakup/splashing). Otherwise, it will recoil in order to minimise the surface energy, and eventually bounce off the surface if there is sufficient kinetic energy available at the end of recoil. Drop impact phenomena are usually characterised by dimensionless numbers such as the Weber number,  $We = \rho v_i^2 D_0 / \sigma$ , where  $\rho$  and  $\sigma$  are the fluid density and surface tension, respectively,  $D_0$  is the equilibrium drop diameter, and  $v_i$  the normal impact velocity; the Reynolds number,  $Re = \rho v_i D_0 / \mu$ , where  $\mu$  is the fluid viscosity; this is sometimes used in combination with the Weber number to yield the Ohnesorge number,  $Oh = We^{0.5} / Re$ ; the Capillary number,  $Ca = \mu v_r / \sigma$ , where  $v_r$  is the retraction velocity.

The classification of impact regimes, reviewed in [10], is still somewhat controversial, due to the complexity of phenomena

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**Nomenclature**

$a$	capillary length, m
$c_p$	heat capacity, J/kg K
$Ca$	capillary number, –
$D_0$	equilibrium drop diameter, m
$g$	gravity, m/s <sup>2</sup>
$H$	drop release height, m
$k$	thermal conductivity, W/m K
$K$	$K$ -number, –
$m$	mass, kg
$Oh$	Ohnesorge number, –
$R_a$	surface roughness, m
$Re$	Reynolds number, –
$t$	time, s
$T$	temperature, K
$u$	theoretical free-fall velocity, m/s
$v$	velocity, m/s
$We$	Weber number, –

**Greeks**

$\delta$	vapour film thickness, m
$\varepsilon$	effusivity, W/m <sup>2</sup> K
$\mu$	viscosity, Pa s
$\rho$	density, kg/m <sup>3</sup>
$\sigma$	surface tension, N/m
$\tau$	characteristic time, s

**Subscripts**

$amb$	ambient
$CR$	critical
$L$	Leidenfrost
$LD$	Leidenfrost, dynamic
$liq$	liquid
$S$	surface
$sat$	saturation
$w$	wall

observed during drop impact on heated surfaces. Different studies focused in turn on the effect of the fluid properties [8], and of the surface wettability [11], morphology, and effusivity (defined as  $\varepsilon = \sqrt{\rho k c_p}$ , where  $\rho$  is density,  $k$  is the thermal conductivity, and  $c_p$  the specific heat) [12–14]. Transitions between impact regimes were studied mostly from an empirical point of view. The onset of secondary atomization was found to depend on the surface effusivity [8,12,15], while a critical value of the  $K$ -number,  $K = We^{4/5} Re^{2/5}$  [16,17] defines the transition to breakup/splashing [18]. Finally, the transition between rebound with secondary atomization and dry rebound, which defines the dynamic Leidenfrost temperature [1], was the subject of experimental works [5–9], while a theoretical model was proposed to estimate the minimum temperature required for rebound at different impact velocities [19]. It was also shown that all of the above transitions are strongly affected by the presence of small amounts (of the order of 100 ppm) of flexible polymers dissolved in the fluid [20–22].

The earliest attempts at constructing a global map of drop impact regimes on heated surfaces were prompted by the need to simulate spray impingement [23], and plotted boundaries between the various impact regimes with respect to the surface temperature and the Weber number. Impact regimes were also mapped with focus on the temporal evolution of the drop morphology rather than on the final outcome [6]. Other qualitative impact regime maps used the surface temperature and the impact Weber number as coordinates [1,24], however transition boundaries between different impact regimes were not defined quantitatively. More recently, the impact regimes of sub-millimetric droplets ( $D_0 < 200 \mu\text{m}$ ) were mapped with respect to the  $K$ -number, and a non-dimensional temperature accounting for the local surface cooling upon impact [25].

A common issue with these maps is that the boundaries between different impact regimes are essentially qualitative, because the space of parameters (usually, the surface temperature and the impact Weber number) is not explored uniformly, with experimental points concentrated in particular regions of interest (for example, to investigate a particular transition). Moreover, different authors may use slightly different definitions of the impact regimes.

A map displaying the impact regimes of water droplets on a heated silicon wafer that covers the surface temperature – Weber number coordinate space more uniformly was proposed in a recent paper [30]. According to this map, no splashing/breakup is

observed even at high Weber numbers ( $We \sim 500$ ), and in general other transitions occur at significantly higher temperatures than in previous works.

This paper presents a unifying classification of drop impact regimes on heated surfaces based on the morphology of the final outcome, which embraces the different impact morphologies reported in the existing literature, but at the same time is simple enough to be used for practical purposes. Based on such simplification, an empirical impact regime map covering uniformly the range of Weber numbers between 0 and 160 and the range of surface temperatures between 100 and 400 °C is presented, and compared critically with existing maps. The proposed map was constructed based on data obtained with water drops of millimetric size impacting on a polished aluminium surface, however can be considered representative of other systems as well.

## 2. Experimental apparatus and procedure

The experimental setup is schematically described in Fig. 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. The needle was positioned above the surface of an aluminium square block (40 × 40 mm) containing two electric cartridge heaters (100 W each) symmetric with respect to the point of impact to ensure a uniform temperature field. The surface was mirror polished with a chemical abrasive (average surface roughness:  $R_a = 0.1 \mu\text{m}$ ). The surface was re-polished at regular intervals, to remove possible oxide layers; after wiping off the polishing fluid, the surface was heated at 400 °C for a few minutes to remove residual traces of solvent. Temperature could be controlled within  $\pm 1$  °C by a PID controller driven by a K-thermocouple placed exactly 1 mm below the point of impact.

Drop weight measurements made with a precision balance (Mettler Toledo MT100) allowed calculation of the drop diameter at equilibrium,  $D_0 = (6m/\pi\rho)^{1/3}$ , where  $m$  is the drop mass, and  $\rho$  the water density: the average value, calculated over 50 samples, was  $3.09 \pm 0.1$  mm. The drop equilibrium radius,  $D_0/2$ , was therefore smaller than the capillary length,  $a = (\sigma/\rho g)^{1/2}$  (2.48 mm for water drops), which is indicative of the competition between surface forces, quantified by the surface tension,  $\sigma$ , and gravity,  $g$ :

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