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Experimental investigation of spray impingement hydrodynamic on a hot surface at high flow rates using phase Doppler analysis and infrared thermography

A. Labergue [*], M. Gradeck, F. Lemoine

LEMTA, UMR 7563, Université de Lorraine, Vandoeuvre-Lès-Nancy 54518, France
LEMTA, UMR 7563, CNRS, Vandoeuvre-Lès-Nancy 54518, France

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ABSTRACT

Large panels of studies have been performed in order to investigate the dynamic behavior of a droplet during the impingement onto a rigid wall. Most of them are dealing with single droplets and only fewer are devoted to sprays, for which several diagnostics were implemented. Moreover, when sprays are involved, the liquid mass flux is generally quite low (on the order of several $kg/m^2/s$) and the case of a cold surface was mainly considered. Therefore, the present experimental work aims at investigating the impingement of sprays onto hot surfaces (up to 800 °C) with liquid mass flux up to 13 $kg/m^2/s$. Specifically, the main objective is to characterize the secondary droplets as a function of the surface temperature, starting from the Leidenfrost regime. To that purpose, a 2D phase Doppler analyzer (PDA) is synchronized with an infrared camera in order to measure simultaneously the time evolution of the local droplets size and velocity distributions with the surface temperature. Six full cone sprays were used in order to obtain a wide range of impingement conditions (normal incident Weber and liquid mass flux). A comparison of the impingement characteristics is also performed when the surface remains at room temperature. Another important point concerns also the effect on the spray flow of the presence of the surface. Results show clearly that the incident droplet trajectories are modified by the presence of the solid wall itself and depend strongly on the temperature surface. The in-depth investigation of the impingement characteristics of the spray is mainly focused on the description of the statistical mean diameter and the mass flux after the impingement. The main results highlight that the mean diameter value of the secondary droplets does not change during the Leidenfrost regime and increases for lower surface temperature. This behavior is strongly correlated to the liquid film formation for temperatures lower than the Leidenfrost point. The expelled mass flux exhibits a similar behavior but a decrease is observed after a given temperature, which can be attributed to the deepening of the liquid, leading to a reduction of the number of expelled droplets.

1. Introduction

Studies of spray-wall interactions have always received a lot of attention due to the numerous industrial processes involving the impingement of droplets onto a solid wall. In some cases, the wall is heated like in a combustion chamber of a direct injection engine or for applications where the dissipation of high heat flux is required (steel industry, cooling of electronics components or nuclear safety issues). In other cases, the surface temperature is close to the liquid one and no heat transfer occurs; it concerns applications such as spray coating or spray painting. In both cases, the hydrodynamics of the impingement is mainly characterized by the generation of the secondary spray (*i.e.* after impact) and the potential formation of a liquid film on the surface. The latter depends on several parameters such as the surface temperature, the relative roughness of the surface and also on the incident droplet properties (viscosity, density, surface tension, diameter, velocity and incident impact angle). Usually, two main dimensionless parameters are used to describe the impact conditions: the Weber and Ohnesorge numbers, respectively defined by $We = \rho U^2 D/\sigma$ and $Oh = \mu/(\rho D\sigma)^{1/2}$ where U and D are the velocity and the diameter of the droplet before impact, μ, ρ and σ are the dynamic viscosity, the mass density and the surface tension, respectively. In addition, in order to account for the influence of the surface temperature, a dimensionless temperature T^* is introduced:

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[*] Corresponding author at: LEMTA, UMR 7563, Université de Lorraine, Vandoeuvre-Lès-Nancy 54518, France.

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Nomenclature

We	Weber number (–)
Oh	Ohnesorge number (–)
K	Mundo number (–)
C_p	specific capacity (J/kg/K)
a	thermal diffusivity (m/s$^{2)}$
k	thermal conductivity (W/m/K)
R	disk radius (m)
e	disk thickness (m)
D	droplet diameter (m)
h	enthalpy (J/kg)
G	liquid mass flux (kg/m^2/s)
q''	heat flux density (W/m^2)
v, w	droplet velocity component (m/s)
r	radial coordinate (m)
T	temperature (K)
t	time (s)

Greek symbols

α	spray angle (°)
λ	fractions (–)
ρ	mass density (kg/m^3)
μ	dynamic viscosity (Pa·s)
σ	surface tension (N/m)

Symbols

*	dimensionless
$\sim$	time average
$-$	arithmetic mean

Subscripts

a	after impact
b	before impact
d	relative to single droplet
l	property of liquid phase
n	normal to the surface
$Leid$	Leidenfrost temperature
sat	liquid saturation properties
sub	surface subcooling
v	property of vapor phase
w	conditions at the disk surface
m	mass
N	number
10	mean diameter
32	Sauter diameter
Ni	relative to the nickel properties

$$T^* = \frac{T_w - T_{sat}}{T_{Leid} - T_{sat}} \tag{1}$$

where T_w, T_{sat} and T_{Leid} are respectively the surface temperature, the saturation temperature of the liquid and the Leidenfrost temperature. The Leidenfrost regime ($T^* > 1$) is characterized by the presence of a vapor layer formed between the liquid and the solid wall, causing a dramatic reduction of the heat transfer. A cold impingement corresponds to a situation where $T^* < 0$. Three main impingement regimes can be observed: rebound, splashing and deposition, the latter contributing to the formation of a liquid film. Introducing the Mundo number, $K = WeOh^{-0.4}$ [1] and using the dimensionless temperature T^*, it is possible to determine empirically the regime associated with a set of impact conditions. Compiling the results of Dewitte [2] and Cossali et.al [3] on a $K - T^*$ diagram for single droplets impinging onto a heated surface, the boundaries delimiting the different regimes can be outlined (Fig. 1).

Only rebound and splashing regimes can be observed in the Leidenfrost regime. For a narrow temperature range corresponding to $0.5 < T^* < 1$, the three regimes may exist. For $T^* < 0.5$, according to the Mundo number value, an incoming droplet may deposit or splash on the surface.

Obviously, the characteristics of the impingement for a spray onto a solid surface are different compared to single droplets. On one hand, the boundaries in Fig. 1, deduced from experiments conducted with single droplets, will more likely be different for sprays. On the other hand, as different droplet diameters or velocities are involved in a spray, the corresponding distribution of the Mundo number could lead to simultaneous different impact regimes for a given surface temperature. Consequently, the properties of the secondary droplets in the case of impinging sprays are expected be different compared to those of a single droplet [4–5].

Due to the multiples parameters and the complexity of the mechanisms of the droplets impingement, a large number of investigations are focused on single droplets impinging on a cold surface [4–8] or on a heated surface [1–3,9–18]. On the contrary, works describing the secondary droplets in the case of spray impingements [19–22]. In fact, studies dealing with sprays impinging onto heated surfaces are devoted to investigate the heat transfer between the liquid and the solid surface as a function of the initial sprays conditions: liquid mass flux or Weber number. In the particular case of a spray, two Weber numbers can be defined: (1) the usual single droplet Weber number We_d based on the diameter of a given droplet size class and the normal velocity of the corresponding class or (2) the mean Weber number $\overline{We}$ based on the arithmetic mean droplet diameter and mean normal velocity. Moreover, a literature review reveals that the value of some operating parameters such as Weber number, liquid mass flux and wall temperature remain relatively low in comparison to standard industrial configurations. Al-Ahmadi [23] and Cox and Yao [24] have used conditions close to industrial operating conditions (droplet diameters up to several millimeters and liquid mass flux up to

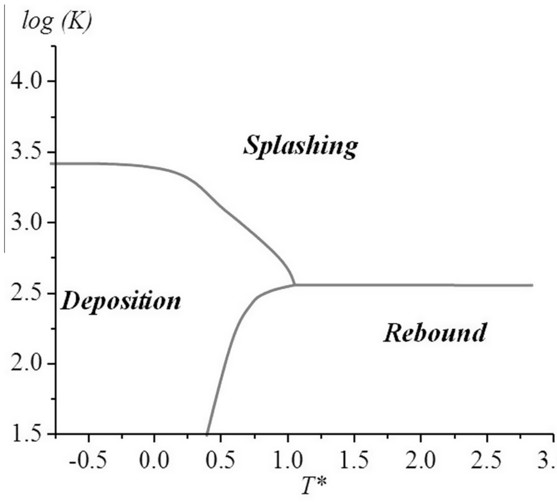

Fig. 1. $K - T^*$ diagram representing the boundaries between the different impact regimes according to the dimensionless surface temperature and the Mundo number from the works [2–3].