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Comparative study of the cooling of a hot temperature surface using sprays and liquid jets

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ABSTRACT

This experimental work aims at investigating the cooling of hot surfaces by using full cone sprays; comparison with the use of a liquid jet is also considered. The wall is a 175 mm diameter nickel disk and 5 mm thickness heated by electromagnetic induction up to about 800 °C. In the case of the sprays, the goal is to link the spray properties with the heat flux removed from the heated surface. For the spray, the influence of the mass flux distribution as well as the droplets properties on the cooling are studied by using three different spray nozzles. The mass flux distribution for each of the sprays is measured with the help of a patternator. The heat removed during the cooling phase is investigated with the use of infrared thermography while the droplet properties are characterized simultaneously by a Phase Doppler system. The Phase Doppler technique is mainly applied to study the statistical properties of the outcoming droplets in the vicinity of the heated surface. A decrease of the outcoming droplets size compared to the incoming one is well observed. Moreover, Phase Doppler device has also highlighted that the presence of the surface may have a significant influence on the upstream spray flow. Compared to the liquid jet, heat flux measurements have clearly demonstrated that the sprays lead a more spatial uniformity of the extracted heat flux and a better cooling efficiency. When spray cooling is considered, the influence of the mass flux on the heat flux and the cooling efficiency is in qualitative agreement with previous studies performed in similar conditions. In addition, a comparative study of performances, in term of liquid consumption and cooling duration, is performed by considering a similar surface temperature decrease for the three sprays and the liquid jet. Among the four experiments, the liquid jet has the longest cooling time as well as the highest liquid consumption. Furthermore, the best performances are reached for the spray having the highest mass flux value.

1. Introduction

The use of water for cooling of hot surfaces in industry is unavoidable when high heat flux dissipation is required. Some emblematic examples are related to nuclear safety issues or to the thermal processing of alloys in steel industry. Cooling processes include pool boiling, impingement of liquid jets or sprays. In steel industry, pool boiling and liquid jets are widely used because they provide high dissipation rates but they have generally failed to ensure uniform cooling. Thus the homogeneity of the metallurgical phase can suffer from defaults.

The use of sprays seems attractive for several reasons: a better spatial uniformity of the cooling can be achieved associated with lower water consumption for the same efficiency in term of heat transfer. Furthermore, lower water consumption involves less energy requirements for pumping and recycling the cooling water and thus an increase of the overall energy efficiency of the process. The experimental studies devoted to water spray cooling cover a wide range of cooling conditions. For practical reasons, the case of deposited droplets [1,2] single or multiple droplets was widely studied and well documented [3–10]. When sprays were used, several configurations where found, such as mono-sized sprays (impulse-jet technique to produce uniform size droplets) [11–15] or sprays polydispersed in size [16–26]. Furthermore, several categories of nozzles are available to generate various sprays with different geometries and liquid densities, droplet size and velocity distributions: full cone, hollow cone, flat fan or air-mist nozzles. However, only few authors have performed quantitative comparisons between the different spraying nozzles [4,21,26].

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Nomenclature

We	We number (–)
c_p	specific capacity (J/kg K)
d	droplet diameter (m)
h	enthalpy (J/kg)
$\dot{m}$	liquid mass flux (kg/m^2 s)
$\dot{M}$	flow rate (l/mn)
q''	heat flux (W/m^2)
u, v, w	droplet velocity component (m/s)
p	liquid pressure (bar)
r	disk radius (m)
T	temperature (K)

Greek symbols

α	thermal diffusivity (m^2/s)
β	spray angle (°)
ε	emissivity (–)
λ	laser wavelength (m)
ρ	mass density (kg/m^3)
μ	dynamic viscosity (Pa s)
σ	surface tension (kg/m^2)
ξ	cooling efficiency (–)

Subscripts

b	laser beam
d	droplet
l	property of liquid phase
$Leid$	temperature at which minimum film boiling heat flux occurs
s	spray
sat	liquid saturation properties
sub	surface subcooling
v	property of vapor phase
w	conditions at front disk wall

In steel industry, the surface temperatures are generally above the Leidenfrost temperature at the beginning of the cooling phase and high water mass flux are required, which involved generally large-sized droplets. Experiments referred in the literature aim at characterizing the heat flux removed from the hot wall in conjunction with the droplets characteristics. Thermocouples inserted in the wall, coupled with an inverse conduction algorithm, are generally used to characterize the wall heat flux [5,6,17–19,26] whereas a granulometer (e.g. Phase Doppler analyzer system) is used to derive the velocity and diameter distributions of the droplets [18,19]. For instance, Al-Ahmadi et al. [26] and Cox et al. [14] have estimated the heat flux removed by sprays using thermocouples under conditions that are close to industry operations (droplet diameters up to several millimeters and mass flux up to 30 kg/m^2 s^{-1} respectively). More recently, infrared thermography (IRT) was also applied to estimate the heat flux extracted from a heated wall by using liquid jets [27], deposited droplets [14,15], single droplets or monodisperse droplet streams [10]. With the same objective, Jia and Qiu [18] have used thermocouples and a PDA device to estimate the heat flux and both incoming and outcoming droplets characteristics respectively. Therefore, they found that the heat transfer depends on the expulsion rate defined as the ratio of the outgoing to incoming masses fluxes. However, the mass flux in this study was low (1.20 kg/m^2 s^{-1} at maximum). Puschmann et al. [20] have realized an overall study by using a 2D-PDA device for the droplet properties and a patternator for the mass flux distribution as well as an IRT method to estimate the heat flux. They well validated their experimental set-up but the mass flux still remains low (5 kg/m^2 s^{-1} in maximum).

Usually, the Weber number and the mass flux are the two common parameters used in order to classify and qualify the cooling of a hot surface by sprays. Fig. 1 depicts the values of the Weber number and the mass flux of the main studies encountered in the literature. It can be observed that very few studies have been performed with high mass flux values [21–26]. In fact, the main studies were operated with a maximum mass flux of about 20 kg/m^2 s^{-1} and with a Weber number range of about [10–1000].

Except Jia and Qiu [18], the majority of the herein mentioned studies are limited to the investigation of the heat transfer issues but the link with the characteristics of the droplets and the hydrodynamic conditions of the impact with the heated surface is generally not investigated. Therefore, the objective of the present work is to compare the cooling properties and to link them with the incoming droplets characteristics and impingement features. In addition, the long term objective of this study is to work as much as possible under the industrial conditions (i.e. mass flux at least equal to 100 kg/m^2 s^{-1}). Thereby, an experimental set-up was specially designed. Nevertheless, before injecting such mass flux values, the present study is limited to a maximum mass flux of about 8 kg/m^2 s^{-1} in order to validate the experimental set-up. In a future paper, similar experiments will be performed by increasing gradually the mass flux. In the present work, three full cone sprays are used in order to vary the mass flux distribution as well as the droplet velocity and size leading to Weber number up to about 800. The operating conditions targeted in the present study are shown in Fig. 1. Additionally, the comparison with cooling by a liquid jet will be also considered. For the three sprays, both the heat flux removed from the wall and the characteristics of the droplets interacting with the heated surface were characterized simultaneously respectively by using a 2D-PDA system and an IRT method combined with an inverse heat conduction model.

2. Sprays facilities

The experimental test rig, sketched in Fig. 2, was designed in order to work at a high water mass flux, approaching conditions used in steel industry for hot surfaces quenching.

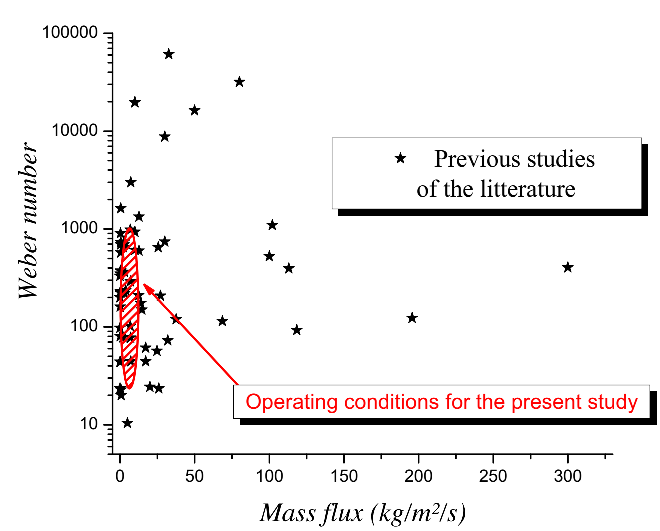

Fig. 1. Classification of the sprays plotted in the 2D-plan *We – mass flux* of the main studies encountered in the literature for sprays cooling.