



## Technical Note

## Optical flow and thermal measurements for spray cooling



Shou-Shing Hsieh\*, Ghia-Wei Chen, Yi-Fan Yeh

Department of Mechanical and Electromechanical Engineering, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan, ROC

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## ABSTRACT

This paper reports an experimental study of DI water and FC-72 dielectric liquid spray cooling heat transfer through the optical measurements of the droplets' local velocity as well as the droplets' temperature distribution during the flight along the downstream prior to impinging on the surface. A micro-particle image velocimetry ( $\mu$ PIV) is used to measure the local velocity distribution along the path, and two-color laser-induced fluorescence ( $\mu$ LIF) is used to characterize the local droplet temperature distribution. Furthermore, the time evolution of the liquid film growth, as well as the steady-state liquid film, is visualized and the thickness is measured.

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## 1. Introduction

High heat transfer cooling technology has received a lot of attention over the years due to the ever-increasing complexities in modern industrial applications, such as the cooling of electronic devices, nuclear power generation, cryogenics and steelmaking processes. Most past researches on spray cooling have mainly focused on the heat transfer characteristics and the effects of the relevant parameters [1–5], especially nucleation boiling and critical heat flux (CHF). Although many experiments dedicated to gaining a better understanding of the spray cooling heat transfer process have been conducted in recent years [6–8], a detailed understanding of spray cooling flow behavior and the heat transfer mechanisms associated with it has yet to be obtained. Previous studies [9] have indicated that the droplet size and local distribution are critical to the optimization of the process parameters. Yang et al. [10] reported an analytical work to determine the thickness of liquid film deposited on a flat surface by a spray under the influence of a secondary gas stagnation flow field. Also, a heat transfer correlation was developed in terms of the film thickness in the nucleate boiling regime. Recently, Martinez-Galván et al. [11] have again found that there is a relation between the variation in the average Nusselt number and the film thickness with the boiling curve during spray cooling.

The measurements of the physical parameters in a spray can require the use of non-intrusive techniques. One of the most common techniques is laser-induced fluorescence (LIF), which is

particularly attractive because it allows for the splitting of the liquid and vapor phases of the working medium. In addition, LIF signals are intense, which results in better detectivity and an improved signal-to-noise ratio. A proper tracer can be used in the planar laser-induced fluorescence (PLIF) measurements of the liquid droplets' mean temperature.

In our work, we present the non-intrusive optical techniques of  $\mu$ PIV (micro-particle image velocimetry) to measure the spray velocity field and  $\mu$ LIF (micro-laser-induced fluorescence) to measure the spray(droplet) detailed temperature/liquid film temperature, and to determine the liquid film thickness through optical measurements. The study involved two main sets ( $\mu$ PIV and  $\mu$ LIF) of experiments in order to provide useful information about the flow and thermal field development of sprays on heated surfaces. The objective of this work was to develop an alternative non-intrusive technique to measure the thermal/velocity distribution and to calculate the heat transfer data, as well as the film thickness, that characterize the spray cooling heat transfer.

## 2. Experiment

## 2.1. Experimental set-up

The experimental facility used in this study consisted of a spray chamber, the measurement system, a flow loop and a data acquisition system. The major area of interest was the insulated copper block, whose one exposed surface (20 cm<sup>2</sup>) served as the heated/impinging surface. Two-cartridge heaters [12] were inserted evenly into the insulated copper plate to generate 300 W of uniform heat load. These two cartridge heaters were connected in a

\* Corresponding author. Tel.: +886 (07) 5252000x4215; fax: +886 (07) 5254215.  
E-mail address: [sshsieh@faculty.nsysu.edu.tw](mailto:sshsieh@faculty.nsysu.edu.tw) (S.-S. Hsieh).

**Nomenclature**

$Bo_m$	modified boiling number, $qH/\mu h_{fg}$	$u_o$	spray exit velocity, m/s
$C_p$	specific heat for spray liquid, kJ/kg°C	$u_p$	spray impingement velocity, m/s
$d_j$	nozzle diameter, m	$We$	spray Weber number, $\rho \mu_p^2 d_{32}/\sigma$
$d_{32}$	Sauter mean diameter (SMD), $\mu\text{m}$	<b>Greek symbols</b>	
$h_{fg}$	enthalpy of evaporation, kJ/kg	$\mu$	dynamic viscosity, Pa s
$k_f$	thermal conductivity of the liquid, W/m°C	$\Delta T_{sat}$	wall superheat, °C
$Nu$	Nusselt number, $(hL)/k_f$	$\delta$	liquid film thickness, m
$\overline{Nu}$	average Nusselt number over the entire subcooled nucleate boiling	$\rho$	density of liquid, kg/m <sup>3</sup>
$q''$	heat flux (Q/A), W/m <sup>2</sup>	$\sigma$	surface tension of spray liquid, N/m
$Re$	spray Reynolds number, $\sigma \mu_o/\mu$	$\theta$	azimuthal direction, °

series, and then this pair was connected to a DC power supply. A variac transformer integrated with a DC power supply was used to supply variable voltage. The heat flux was calculated from the voltage, current and heater area. Except for the heated surface, the entire copper plate was insulated by a 5 mm fiberglass ( $k = 0.11$  W/m K) blanket to avoid heat loss. In order to measure the heater surface temperature, five T-type 80  $\mu\text{m}$  thermocouples were spaced 1 mm apart along the axis of the copper block. The upper thermocouple was positioned 0.05 mm beneath the heater surface. These five thermocouples were inserted into 0.6 mm diameter holes drilled on the copper block surface. The holes were filled with a resin with a high thermal conductivity ( $\sim 11$  W/m K) so as to avoid air gaps inside the holes. The heater surface temperature could, therefore, be determined based on 1-D heat conduction and extrapolation of the abovementioned five measured temperatures.

The working media used were DI water and FC-72, respectively, which were sprayed over the target surface at a definite distance of 170 mm (DI water) and 30 mm (FC-72) with a circular full-cone nozzle manufactured by IKEUCHI, Japan. The model used had a diameter of 200  $\mu\text{m}$ . The mass flow rate was determined by the pressure drop (300 kPa, 350 kPa and 2000 kPa) across the spray nozzle; a pressure transducer was connected in front of the nozzle to measure the operating pressure. In order to measure the saturation condition in the chamber, one pressure transducer and two T-type thermocouples (one for the spray exit temperature and one for monitoring the chamber environment temperature) were used. A data requisition system HP34970A with a multiplexor module HP34901A was fed with the signals from the thermocouples, the pressure transducers and the coolant flowmeter. The degree of subcooling in this study was about 77 °C for water and 33 °C for FC-72, and it was controlled by fixing the spray exit temperature.

## 2.2. Temperature image observation and film thickness measurement

DI water and FC-72, as the working fluids, were previously seeded with a low concentration (150  $\mu\text{M}$ ) of rhodamine B (Sigma-Aldrich Corp., USA). The fluorescence of rhodamine B, which can be easily induced by the green line of an argon ion laser, is broadband, and its temperature sensitivity is strongly dependent on the wavelength. The two-color laser-induced fluorescent optical system was used following Hsieh and Huang [13]. The measurement volume, by means of particle image velocimetry (PIV), also allowed the spray droplet velocity to be measured (also see [13]). The droplet mean temperature was obtained using a measurement volume diameter comparable to the spray droplet diameter itself and by averaging the fluorescence signal over the overall transit time of the droplet in the measurement volume. Based on the

measurement techniques [13,14] mentioned above, a  $\mu\text{PIV}/\mu\text{LIF}$  was developed and set up for the spray velocity and thermal field measurements, including the progression of the spray due to the hot plume caused by the heated surface, the emitted vapor due to evaporation and the droplets bouncing/splashing on the heated surface.

Regarding the  $\mu\text{LIF}$  experiment, fluorescence imaging of the rhodamine B dye (diffusion coefficient =  $2.8 \times 10^{-10}$  m<sup>2</sup>/s at a concentration of  $1.5 \times 10^{-4}$  M) was conducted using a Leica DMILM fluorescence microscope equipped with a 10x objective, a mercury lamp, a rhodamine B filter set and a Dentec 80C77 Hisense  $\mu\text{LIF}$  CCD camera ( $1344 \times 1024 \times 12$  bit) by which the transformation of temperature fields in different areas (optical planes) was recorded. Digital images were acquired and transferred to a PC and successively processed and analyzed. The intensity values of the captured images were converted to temperature values using intensity versus temperature calibrations. In addition to the  $\mu\text{LIF}$  thermal visualization, traditional thermocouple temperature measurements, as stated previously, were used to calculate the spray heat transfer.

In order to measure the film thickness, a high speed camera (500 fps,  $752 \times 376$  pixels resolution), with a prime lens of 200 mm implemented with a long distance microscope, was used. Solo PIV-II Nd: YAG laser light was used for lighting. The film thickness, with values of 0–2.7 mm (DI water) and 0–0.14 mm (FC-72) at a location beneath a single-cone spray with applied heat input (0–300 W), was measured for both a transient and steady state.

## 2.3. Data reduction and uncertainty analysis

Experiments were performed at 1 bar to ensure that the pressure inside the chamber was at an atmospheric level at all times. Both the transient and steady state ( $\geq 30$  min) in each experiment were taken and recorded. In addition, the repeatability of each experiment was ensured. In the study, the liquids used were DI water and FC-72, respectively which had a temperature measurement uncertainty of  $\pm 0.1$  °C. Based on the 1-D Fourier conduction law, the heat flux,  $q''$ , was calculated by the temperature gradient along the axial direction. This can be expressed as  $q'' = (k\Delta T)/s$ , where  $\Delta T$  and  $s$  are the temperature difference and the distance between two thermocouples, respectively, and  $k$  is the thermal conductivity of the heating plate. Therefore, the heat transfer coefficient,  $h$ , of spray cooling can be obtained by the form  $h = q/(T_s - T_{sat})$ , where  $q$  is the heat flux,  $T_s$  is the heated surface temperature and  $T_{sat}$  is the saturation temperature of the liquid spray. The uncertainty of the average surface temperature due to the extrapolation [12] was about  $\pm 1.2\%$ . The flow meter had a measurement uncertainty of 0.1% of the total mass flow rate. Heat loss was estimated at less than 3% of the electrical power input to the

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