International Journal of Heat and Mass Transfer 92 (2016) 190–205

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Droplet impact dynamics and transient heat transfer of a micro spray system for power electronics devices

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ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form 25 August 2015
Accepted 25 August 2015
Available online 10 September 2015

Keywords:
Droplet impacting dynamics
ITO heater
Spray heat transfer
Power electronics device

ABSTRACT

We present a study on the instantaneous heat transfer and droplet impact dynamics caused by multiple streams of water impinging on a polished surface with a constant heat flux (0.1–0.9 W/cm^2) heating applicable to power electronics' thermal configuration design. A multiple spray was produced by a commercial piezoelectric atomization plate (power = 1.5 W and frequency 104 kHz) with three different nozzle arrays of $d_j = 7\ \mu m$, $10\ \mu m$ and $35\ \mu m$ and a corresponding mass flow rate of 4.42×10^{-5} kg/s, 1.11×10^{-4} kg/s and 1.15×10^{-4} kg/s, respectively. A heater consisting of an ultra-thin layer (~200 nm) of Indium Tin Oxide (ITO) combined with quartz glass (0.3 mm thickness) substrate was used to characterize the cooling history and droplet impact hydrodynamics. Through optical visualization from a bottom view, the transient impact droplets' morphology and the, surface temperature distribution, were measured and extracted to obtain the evolved film thickness. The effects of nozzle diameter, in addition to the spray height and the initial surface temperature on heat transfer for very short periods of time (<1 s), were studied. Furthermore, the resultant transient (~1 s) cooling performance and heat transfer coefficient were secured and discussed.

1. Introduction

Spray cooling is an efficient, powerful and high heat removal means widely used in many industrial processes. With the rapid growth of the microelectronic industry and a movement towards manufacturing more advanced and high powered devices, thermal management becomes an ever greater concern. Generally, spray cooling uses a spray of small droplets impinging on a heated surface to remove large amounts of heat by taking advantage of evaporation, including substantial convective heat transport via droplet impingement [1]. Frequently, the essential requirements for many electronic power devices include heat flux which can reach up to 100 W/cm^2 at a small surface superheat and a low mass flow rate [2–5]. These are often essential requirements for many electronic power devices, including LEDs [6].

Many relevant studies have been carried out over the last decades. Chen et al. [7] conducted numerous experiments and concluded that three important parameters of the spray characteristics: droplet size, mass flux and droplet velocity, affect the spray's cooling performance. Al-Ahmadi et al. [8] found that the Leidenfrost temperature and critical heat flux (CHF) are strong functions of the spray mass flux. The effects of the spray pattern on the local heat transfer in spray cooling were studied by Abbasi et al. [9]; they found that a higher local droplet flux caused higher local dynamic pressure on the heated surface. Consequently, this resulted in a higher local heat transfer coefficient (HTC). Wendelstorf et al. [10] showed that the HTC in film boiling is a function of volumetric spray flux, as well as the surface temperature. Investigators believe that the spray cooling performance and CHF usually depend on a number of parameters, including: nozzle type, spray height, heater surface condition, working fluid and droplet dynamics [3,11,12].

The physical process of spray cooling, due to the impact of in-flight droplets impinging onto a heated surface, may consequently lead to splashing, spreading or rebounding [13]. Obviously, the rebound process would result in decreased liquid cooling capacity and efficiency. The impinging droplets spread on the surface can form a continuous liquid film. At a high wall superheat, a thin vapor layer can form under the droplets or thin liquid films due to boiling [14]. Previous studies [15,16] indicated that the droplet size and local distribution, as well as the droplet's velocity, are critical factors governing the droplets' flight time and the spray's heat transfer performance. Another parameter that plays an important role in the spray cooling heat transfer is the film's thickness [17]. The film's thickness can characterize heat transfer regimes, and this may be a good indicator of the changes in boiling heat transfer regimes during spray cooling because when the phase change

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.08.099
0017-9310/

Nomenclature

A_s	heater's surface area, cm^2
C_p	specific heat, kJ/kg K
d_c	diameter of crater/spreading diameter, mm
d_j	diameter of nozzle hole, μm
d_p	average (d_{10}) droplet impact diameter, μm
d_{10}	average droplet diameter, μm
h	local heat transfer coefficient, W/m^2 K
h_{av}	average heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
m	total mass flow rate, kg/s
Q_0	volumetric flow rate, cm^3/s
Q_1	total heat transfer rate, W
Q_2	heat loss, W
Q''	volume flux, cm^3/cm^{2}s
q''	heat flux, W/cm^2
T	heater's center surface temperature, K
T_a	ambient temperature, K
T_c	heater's average surface temperature, K
t	time, ms
u_m	measured spray velocity at the nozzle (single) exit, m/s
u_p	droplet impact velocity, m/s
We_p	Weber number, $\rho u_p^2 d_p/\sigma$
Z	a spray height, mm
x, y, z	coordinates, m
Greek symbols	
ρ	density of liquid, kg/m^3
σ	surface tension, N/m
μ	viscosity of liquid, Ns/m^2
Δt	time interval, ms
Subscript	
av	average
c	heater surface/spray liquid layer
cu	copper
j	nozzle exit
m	measured
o	volumetric flux
p	impact
s	saturation
w	wall

occurs, the thickness of the film that is formed not only refers to the liquid phase, but also to the vapor phase of the bubble inside it, which results in increased film thickness.

Although the currently-used LED has increased the photo electric conversion efficiency, more than 80% of the electrical power supplied to LED devices still converts to wasted heat. Normally, the maximum junction temperature of LED chips should be cooled to a suitable temperature, below 150 °C. However, it was found for a 100 W integrated Chip-on-Board (COB) LED, the junction temperature can be up to 1000 °C without proper thermal management [18]. Therefore, a junction temperature higher than 200 °C could happen frequently. Moreover, with COB LEDs becoming more popular, more than 50 W/cm^2 of wasted heat needs to dissipate, which could involve several regimes of boiling heat transfer during spray cooling for power electronics.

Because of the tremendous heat dissipation in high-powered applications, special attention must be given to thermal management to ensure a reliable and successful LED design. Many researchers [19,20] have explored new forms of LED packaging designed to improve heat dissipation, thus extending bulb life and increasing reliability. So far, the existing technology does not appear to effectively overcome the thermal issues associated with high powered LEDs [21].

To date, most studies on spray heat transfer have focused on the effects of the spray's cooling performance. Very little research has been conducted with respect to the thermal effects related to the spray's characteristics in spray cooling, especially on how the surface temperature influences the impacting droplet formation [1]. With this motivation, this study aims to explore the effects of impinged surface temperature on the impacting spray droplets' dynamics, as well as the associated spray's heat transfer/cooling performance, by using both μPIV and thermocouple/IR measurements. The results of the study may provide useful data for a micro spray closed cooling system in order to effectively achieve heat removal of high powered electronics.

2. Experiments

In order to achieve the goal of the present study, an experimental setup was designed and developed for visualizing and measuring droplet impact typology and morphology, and the surface temperature through micro-particle imaging velocimetry and thermocouple measurements incorporated with IR thermography to characterize droplet spray impact and heat transfer behavior. The experimental facility of the study consists of four parts: (1) a spray atomization system, (2) an ITO/quartz heater, (3) a spray chamber and (4) a spray characterization and data acquisition system.

2.1. Spray atomization system

Fig. 1 shows the atomizer (micro-nozzle plate), with some relevant dimensions and sizes listed in Table 1, employed in this study for three different micro-nozzle diameters: d_j = 7, 10 and 35 μm. The water spray issues from a micro-nozzle (approx. 2000 microholes) by a piezo-electric (PZT) micropump (power = 1.5 W, resonance frequency: 104 ± 5 kHz). Details on the PZT micro-nozzle plate's structure can be found in Hsieh et al. [6]. Under the same working conditions as for a PZT atomization plate (1.5 W/104 kHz), there were three different spray mass fluxes applied, as listed in Table 1, which were measured by a measuring cylinder and a stop watch for each experimental run, in order to obtain total volumetric flow rates. In the experiments, the spray nozzle was pointed downward and perpendicular to the target/heater's surface. The nozzle-to-target distance, called the spray height, Z, is defined as the distance from the nozzle tip, or exit, to the target/heater's surface.

2.2. ITO/quartz heater system

For the heat transfer experiment, an ITO/quartz glass heater was designed, fabricated and tested. The heater was made by coating a thin layer of 200 nm of Indium Tin Oxide (ITO) onto a 0.3 mm thick quartz glass substrate, as shown in Fig. 2(a), to achieve a sheet resistance of about 90–100 Ω. An AC power supply, via a Variac transformer, was applied through a two-edge copper electrode wire (diameter ~0.5 mm) connected with an electrically conductive silver epoxy to the surface of the ITO film. Voltage (V) and current (I) across the ITO heater were measured, and the actual heat flux through the ITO heater was monitored in the data acquisition system. The quartz substrate was 30 mm × 32 mm, the surface