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Microspray flow/thermal characteristics via a micro-piezoelectric atomizer with single and multiple arrays of micronozzles

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ABSTRACT

An experimental study on the flow characteristics (only for a single microhole) and cooling performance (multiple array of microholes) of water spray impingement on a polished copper plate using a commercial piezoelectric (PZT) atomizer with multiple arrays of micronozzles (~900 holes) was conducted. Microholes of $d_j = 35\ \mu m$ were used and tested with a total volumetric flow rate of 0.361–22.5 cm^3/min and a corresponding mass flow rate of 6×10^{-6} kg/s–3.7×10^{-4} kg/s using seven spray heights of 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm and 90 mm. μPIV and IPI optical velocimetry, as well as temperature distribution and a droplet size analyzer, were used to measure the downstream local velocity and temperature profile during the spray flight and its associated droplet size distribution for single and multiple arrays of micronozzles. Results of the flow characteristics show that a well-mixed atomization can be found at a spray height of 50 mm, and the spray pattern keeps its symmetry as the flow proceeds downstream. A very rapid cooling rate of −15 °C/s can be reached at the critical heat flux (CHF) for $d_j = 35\ \mu m$ with a spray height of $H = 50$ mm. The effect of the spray height was examined, and it was found that the best cooling performance for a spray height of 50 mm with a CHF can be up to 259 W/cm^2 (steady) and 209 W/cm^2, respectively.

1. Introduction

Spray cooling has emerged recently as a primary technology for thermal management of next-generation high power density electronic devices due to the rapid growth in demand. Its key technical merits include a high heat transfer, small coolant inventory, uniformity of heat removal, low superheat and no thermal resistance with heating surfaces among the realistic heat dissipation methods, such as forced convection/flow boiling in the microchannel heat sink, heat pipe/or vapor chamber and jet impingements [1–3]. However, the complex nature of thermal hydraulic processes on spray cooling with or without a phase change, i.e., either boiling or non-boiling, is still not well understood. Three different regimes have been characterized in boiling spray cooling: nucleation from surface and secondary sites, convection heat transfer and direct evaporation from the liquid film surface [4,5]. Many studies have been conducted on the influence of spray parameters on cooling performance. It was found that the spray heat removal rates usually depend on a number of parameters including the nozzle type, spray height, heat surface working conditions and droplet dynamics [1,6,7]. Even though the aforesaid factors govern the amount of heat that can be removed, the essential heat transfer mechanism via spray cooling is still difficult to identify.

With the growth of the microelectronics industry, thermal management for one of the high power density devices, the LED, becomes an ever greater concern because it has been widely used for light illumination due to its well-known characteristic of least electricity consumption among light illuminating appliances. Although the currently used LEDs have increased photoelectric conversion efficiency, more than 80% of the electrical power supplying LED devices still converts to waste heat that needs to dissipate [8,9]. In addition, as chip-on board (COB) LEDs become more popular, a much higher amount of waste heat needs to be removed very rapidly, which also means that there is an essential need to have a proper cooling method (to remove) with proper coolants to absorb the waste heat. In order to improve the LED's illuminating efficiency, heat dissipation technology [10–13], as well as fast heat removal requirements, becomes more stringent than ever before. The selection of an appropriate cooling technique is based on a definite application as well as specification, and several critical factors should be met, such as the maximum allowable temperature, the total heat duty and the use of space for a working environment [14]. Among the cooling technologies being used, spray cooling has been proven to be the most efficient and powerful means possible [3,8,15] to meet the above-stated, unresolved thermal management issues for high powered LEDs.

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Nomenclature

A	heater's surface area, cm^2
d_j	diameter of nozzle hole, μm
d_{32}	Sauter mean diameter, μm
H	spray height, mm
h	heat transfer coefficient, $W/m^2 K$
k	thermal conductivity, W/m K
m	total mass flow rate, kg/s
Q_{vol}	volumetric flow rate, cm^3/s
Q''_{vol}	volume flux, $cm^3/cm^2 s$
q''	heat flux, W/cm^2
Re_{dj}	Reynolds number, $\rho u_0 d_j/\mu$
T_a	ambient temperature, °C
T_w	heater's surface temperature, °C
T_l	inlet liquid temperature, °C
T_{sat}	liquid saturation temperature, °C
t	time, s
u_c	measured spray centered velocity along the downstream, m/s
u_0	measured spray velocity at the nozzle (single) exit, m/s
u_p	droplet impact velocity, m/s
We_{dj}	Weber number, $\rho u_p^2 d_j/\sigma$
x	distance between two thermocouples, mm
z	spray downstream distance, mm

Greek symbols

ρ	density of liquid, kg/m^3
β	spray angle, °
σ	surface tension, N/m
μ	viscosity of liquid, Ns/m^2
ΔT	temperature difference between two thermocouples, °C
ΔT_s	$T_w - T_{sat}$, °C

Advancements in microfabrication processes have led to many creative ideas and innovations in spray atomization and its related technologies. Therefore, the technique of atomization and the resultant spray flight profiles seem quite diverse depending on the choice of the nozzle type and atomization mechanism [16]. One pressure atomization can be accomplished by using a piezoelectric ultrasonic ring actuator with multiple arrays of micronozzles (approx. 2000 holes) in which a circular spray can be created through a full cone where most of the droplets' coverage is along its circumference. Moreover, as electronic packing becomes more compact and the LED's power continues to increase, a more efficient heat dissipation, especially for a much smaller space, becomes quite challenging. Again, the selection of a nozzle type with appropriate auxiliary components, as well as cooling technology, is very crucial. Due to its relative advantages compared to those of its competitors, such as high speed, high flow rate, low power consumption, simple structure and compactness, the PZT actuated ultrasonic atomizer has been widely used in inkjet printing, painting and medical care for droplet generation [17–19]. However, its application in spray cooling [20] for power electronic devices is quite limited [8,10].

Despite the aforesaid merits, a spray cooling process is essentially complex and complicated as iterated previously, which is the result of a lack of understanding of the underlying mechanisms and the primary and variable parameters that govern spray flow characteristics and cooling performance [21], especially for micronozzles ($d_j < 100\,\mu m$). It is known that the primary parameters and variables that affect spray cooling performance include the mean droplet size, mean droplet velocity and impact velocity for hydrodynamic aspects and geometric variables, such as nozzle diameter, spray height, target surface conditions, etc. [22,23]. Our understanding of the heat transfer mechanism governing heat removal, flow characteristics during the spray flight and impact on the target surfaces with a microspray is quite limited due to

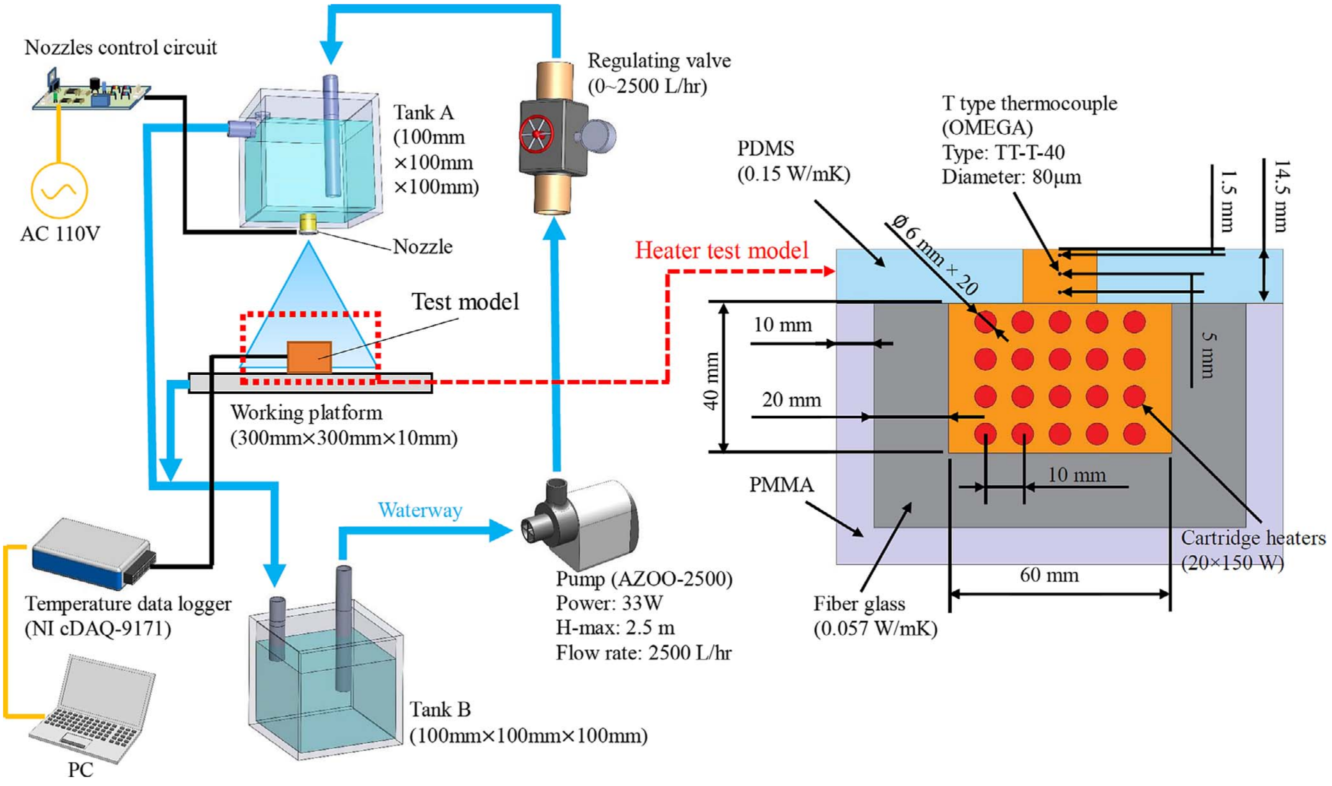

Fig. 1. Schematic of the flow loop.