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Experimental study on optimal spray parameters of piezoelectric atomizer based spray cooling

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ABSTRACT

Piezoelectric atomizer could enhance heat transfer of spray cooling at low flow rate through improved atomization of liquid droplets. To optimize the heat transfer performance of piezoelectric atomizer based spray cooling, a novel piezoelectric atomizer was designed in this paper. The piezoelectric atomizer was composed of two piezoelectric ceramic films (110 kHz) and a stainless steel micropore disk with different outlet diameters of 5 μm, 7 μm, 9 μm, 20 μm and 25 μm (corresponding flow rates of 0.5 mL/min, 1.0 mL/min, 3.8–5.0 mL/min, 11.0–16.0 mL/min and 20.0–29.0 mL/min, respectively). The effects of micropore outlet diameter, volumetric flow rate and spray height on surface temperature distribution, heat flux and the spray cooling efficiency were studied. It was found that the volumetric flow rate increased with the increase of micropore outlet diameter. As the flow rate increased, the heat flux increased but the spray cooling efficiency decreased as a sacrifice. The correlation between spray cooling efficiency/heat flux and flow rate (range from 0.5 mL/min to 29.0 mL/min) of all atomizers could be generalized into one exponential decay/growth curve. An optimal diameter of 9 μm could achieve high heat flux of 123.8 W/cm^2 at a relatively low volumetric flow rate of 5.0 mL/min, and the corresponding spray cooling efficiency was as high as 53.8%. For each atomizer, there was an optimal spray height which differs with the micropore outlet diameter.

1. Introduction

Advances in electronic systems and many modern applications, such as computer data centers, avionics, lasers and X-ray medical systems, are becoming increasingly dependent on high heat flux cooling techniques. Compared with forced convection, pool boiling, jet impingement and etc, spray cooling is an efficient and powerful method for high heat flux removal due to its advantages such as high heat flux removal capacity, low coolant mass flux, no boiling hysteresis, and so on [1–4].

In order to improve spray cooling heat transfer and optimize the efficiency of liquid usage (spray cooling efficiency), numerous studies have focused on the effect of spray parameters on spray cooling [5–10]. Among these studies, many researchers have studied the effect of spray flow rate on the heat transfer performance. Karapetian et al. [11] found that the effect of cryogen flow rate was dominant on the maximum heat flux. Chen et al. [12] measured the spray cooling efficiency of the spray system and concluded that to achieve the maximum CHF while using the minimum quantity of water, it is suggested to select nozzles that produce droplets diameter as small as possible and droplets velocity as high as possible. Cheng et al. [13–16] studied the effect of spray flow rate (range from 26.7 mL/min to 91.7 mL/min) on surface temperature experimentally and numerically. They found that with the increase of spray flow rate, the film thickness and the surface temperature decreased accordingly. Hou et al. [17,18] studied the effect of flow rate on CHF and spray cooling efficiency. The maximum CHF of 117.2 W/cm^2 was achieved with R134a at flow rate of 356 mL/min. It was concluded that with the increase of flow rate, the CHF increased but the spray cooling efficiency decreased.

However, all the studies mentioned above used pressure swirl nozzles to produce the spray. The inlet fluid pressure (proportional to the flow rate) should be very high to achieve good atomization performance which is essential to achieve high heat flux [12]. But the spray cooling efficiency is very low with large flow rate [18].

To solve the problems mentioned above, the piezoelectric atomizer has been used by some investigators to enhance heat transfer at low flow rate through improved atomization of liquid droplets during spray cooling. The atomization principle of piezoelectric atomizer is using the piezoelectric effect to break up the streams of liquid columns into droplets of uniform size. And the droplet parameters are controlled by the frequency of the pulse, applied voltage, micropore outlet diameter and flow rate [19–21].

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Nomenclature

$c_{p,f}$	specific heat capacity of water, kJ/(kg.K)
h	heat transfer coefficient, W/(cm^2.K)
h_{fg}	latent heat of vaporization of water, kJ/kg
q	heat flux, W/cm^2
Q	volumetric flow rate of water, mL/min
T_{surf}	heating surface temperature, °C
T_{inlet}	inlet temperature of the working fluid, °C
Greek letters	
λ	heat conductivity, W/(m.K)
ρ_f	liquid density, kg/m^3
η	spray cooling efficiency, %
δ	distance between two layers, mm

So far, spray cooling using piezoelectric atomizer has been proved to be a promising heat dissipation method at low flow rate. Heffington et al. [22,23] applied a vibration-induced droplet atomizer to two-phase water spray cooling system for integrated circuits. Heat flux as high as 420 W/cm^2 was achieved with the input power less than 3 W. Huang et al. [24] experimentally studied the spray cooling heat transfer performance using piezoelectric (PZT) actuator in vacuum. Heat flux was achieved as 50.3 W/cm^2 at a water flow rate of 1.2 mL/min. Soriano et al. [25,26] designed a piezoelectric droplet generator with the ability to adjust parameters such as droplet impingement frequency, droplet diameter, droplet velocity, and spacing between adjacent impinging droplet streams. The effects of droplet frequency, fluid flow rate, and fluid temperature on heat flux of spray cooling were also presented. The heat flux of 25 W/cm^2 with working fluid HFE 7100 was achieved at flow rate of 4.2 mL/min. Lu et al. [27] developed a piezoelectric micro-dispenser cooling system to solve the overheating problem inside vehicles. Heat flux was achieved as 1000 W/m^2, with water flow rate of 4.0 mL/min and input power of 4 W. Andrew et al. [28] utilized piezoelectric materials to analyze the thermal performance of low Reynolds number jet impingement where the net flow was provided from an oscillating piezoelectric diaphragm. They found correlations to estimate the most efficient placement and operation for a desired cooling effect. Chen et al. [29,30] designed a micro piezoelectric actuator which showed a higher droplet jetting rate and cooling efficiency in the droplet evaporative cooling of three-dimensional space. Hsieh et al. [31] proposed a microspray-based cooling system for the thermal management of high-power LEDs. Heat flux was achieved as 7.81 W/cm^2, with water flow rate of 31.8 mL/min.

In summary, piezoelectric atomizer based spray cooling is an efficient and powerful cooling method among the existing technologies. However, limited works have focused on the spray cooling efficiency of piezoelectric atomized spray cooling, and little works have studied the optimal spray parameters (such as micropore outlet diameter, spray height and spray flow rate) on the heat transfer performance of piezoelectric atomizer based spray cooling. Hence, in order to optimize the heat transfer performance as well as spray cooling efficiency of piezoelectric atomizer based spray cooling, a piezoelectric atomizer was designed in this paper. Considering the effect of micropore outlet diameter, five piezoelectric atomizers with micropore outlet diameters of 5 μm, 7 μm, 9 μm, 20 μm and 25 μm were produced (corresponding flow rates of 0.5 mL/min, 1.0 mL/min, 3.8–5.0 mL/min, 11.0–16.0 mL/min and 20.0–29.0 mL/min, respectively). The effects of spray height and spray flow rate on the cooling performance (heat flux and surface temperature distribution) and spray cooling efficiency were also analyzed in the experiments.

2. Experimental system

2.1. Piezoelectric atomizer

In this study, water spray is produced by a novel designed piezoelectric atomizer. The atomization principle of this piezoelectric atomizer is using piezoelectric effect to transform electronic energy into vibration energy and break up the streams of liquid jets into droplets of uniform size. Here, the piezoelectric atomizer is composed of a piezoelectric disk, a holding device and a high frequency AC circuit. As shown in Fig. 1, the piezoelectric disk consists of two circular piezoelectric ceramic films (thickness: 0.3 mm, resonance frequency: 110 kHz) and a stainless steel micropore disk (thickness: 0.05 mm). During atomization process, the micropore disks are oscillated by piezoelectric ceramic films energized with a high frequency AC circuit (output voltage: 55 V_{p-p} AC, frequency: 110 kHz, input voltage: 5 V DC). There are about 2000 micropores on the stainless steel micropore disk. To study the effect of micropore outlet diameter on the cooling performance, six piezoelectric atomizers with different outlet diameters of 5 μm, 7 μm, 9 μm, 20 μm, 25 μm and 30 μm are presented in this paper. Fig. 2 shows the microscope photographs of micropore disks with different outlet diameters, and the relevant dimensions and corresponding flow rates are listed in Table 1. During the experiment, 6# atomizer failed to atomize water into spray because the liquid column is too big that the piezoelectric disk cannot oscillate it. This is the reason why atomizers with micropore diameters bellow 30 μm are used in this paper and the spray cooling heat transfer analysis below only focus on the former five atomizers. As listed in Table 1, the volumetric flow rates of these five piezoelectric atomizers are 0.5 mL/min, 1.0 mL/min, 3.8–5.0 mL/min, 11.0–16.0 mL/min and 20.0–29.0 mL/min, respectively. It is concluded that the volumetric flow rate and the range of flow rate increases with the increase of micropore outlet diameter. Moreover, when the micropore outlet diameter exceeds 20 μm, the increase trend of flow rate becomes faster. The photograph of piezoelectric atomizer is shown in Fig. 3. The holding device is composed of a stainless steel plate and two silicon sheets. The stainless steel plate could connect the atomizer with the water supply system. The silicon sheets are flexible solids so that they could not only fix the piezoelectric disk but also allow the vibration of piezoelectric disk.

2.2. Spray cooling system

The piezoelectric atomizer based spray cooling system established in this paper is shown in Fig. 4. The system consists of water supply system, piezoelectric atomizer, heating system and data acquisition system. In experiments, the working fluid water is pumped into the spray chamber, sprays out by the piezoelectric atomizer introduced in Section 2.1. The spray droplets impact the heating surface, some of which rebound off the surface, and others adhere to the surface, forming a water film on the heating surface. The water film washes the heating surface and removes heat from the surface by film-surface convection and water film evaporation heat transfer.

As shown in Fig. 5, the heating surface is the top surface of a copper block which is heated by five electric heating rods (each power of 2000 W) in the block. The copper block is surrounded by insulation materials to achieve one dimensional heat transfer