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 (110kHz) and a stainless steel micropore disk with different outlet diameters of 5 μ m, 7 μ m, 9 μ m, 20 μ m and 25 μ m (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 μ m could achieve high heat flux of 123.8 W/cm² 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.

Keywords: spray cooling; low flow rate; piezoelectric atomizer; spray cooling

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efficiency; high heat flux removal.

Nomenclature

$c_{p,f}$ specific heat capacity of water, kJ/(kg.K)

h heat transfer coefficient, W/(cm².K)

h_{fg} latent heat of vaporization of water, kJ/kg

q heat flux, W/cm²

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/m³

η spray cooling efficiency, %

δ distance between two layers, mm

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/cm² 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].

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/cm² was achieved with the input power less than 3W. 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/cm² 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/cm² 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/m², with water flow rate of 4.0mL/min and input power of 4W. 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/cm², 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 5μm, 7μm, 9μm, 20μm and 25μm 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: 0.3mm, resonance frequency: 110 kHz) and a stainless steel micropore disk (thickness: 0.05mm). During atomization process, the micropore disks are oscillated by piezoelectric ceramic films energized with a high frequency AC circuit (output voltage: 55V_{p-p} AC, frequency: 110 kHz, input voltage: 5V 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 can not 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 2000W) in the block. The copper block is surrounded by insulation materials to achieve one dimensional heat transfer in the upper copper cylinder. To obtain the heating surface temperature and heat flux, four layers of thermocouples are arranged 1 mm, 6mm, 11mm and 16mm below the heating surface respectively. In each layer, there are three thermocouples arranged at different position of the cylinder center with 120° separately staggered. The radial distances from the thermocouples to the center axis of the heater are 0mm, 2mm, and 4mm respectively. The temperature data is collected by Agilent 34970A.

2.3 Data calculation and uncertainty analysis

In this study, the heating surface temperature, heat flux and spray cooling efficiency are crucial parameters of interest in evaluating the heat transfer performance.

The heating surface temperature is calculated by temperatures of each layer using the extrapolation method.

$$T_{\text{surf}} = T_1 - \frac{\delta_1(T_i - T_j)}{\Delta\delta} \quad (1)$$

where, T_1 is the temperature of the first layer; T_i and T_j are the temperature of two layers i and j , respectively; δ_1 is the distance from the first layer to the heating surface; $\Delta\delta$ stands for the distance between the above two layers i and j ; i and j stands for the number of two layers ($i, j=1,2,3,4, i>j$). It is assumed that the heat conduction through the upper copper cylinder can be regarded as one-dimensional, so the heat flux q can be calculated by the temperature gradient on axial direction according to the Fourier conduction law, as following:

$$q = \frac{\lambda(T_i - T_j)}{\Delta\delta} \quad (2)$$

where, λ is the thermal conductivity of copper; T_i and T_j are the mean temperature of two layers i and j , respectively; $\Delta\delta$ stands for the distance between the above two layers. The heat transfer coefficient h of spray cooling can be defined as:

$$h = \frac{q}{T_{\text{surf}} - T_{\text{inlet}}} \quad (3)$$

where, q is the heat flux; T_{surf} is the heating surface temperature; T_{inlet} is the inlet temperature of the working fluid.

Spray cooling efficiency is another important heat transfer performance parameter which expresses the utilization efficiency of water spray. It is defined as the ratio of experimental heat flux to the maximum heat flux that can be removed by the spray, as following:

$$\eta = \frac{qA}{\rho_f Q (c_{p,f} \Delta T + h_{fg})} \times 100\% \quad (4)$$

where, q is the heat flux; A is the area of heating surface; ρ_f is the density of water; Q is the volumetric flow rate of water; $c_{p,f}$ is the specific heat capacity of water; ΔT is

the difference of saturation temperature and inlet temperature of water; h_{fg} is the latent heat of vaporization of water.

The measurement uncertainty in this study is dependent on the measurement of distance between the thermocouple layers, temperature readings by thermocouples, and the volumetric flow rate of the pump. The thermocouples were calibrated in a constant temperature bath before tests, and the uncertainty of the calibrated thermocouples is $\pm 0.2^\circ\text{C}$. The uncertainty of distance is $\pm 0.1\text{mm}$. The uncertainty of volumetric flow rate after calibration is $\pm 0.1\text{ mL/min}$. Therefore, according to the error transfer formula:

$$\sigma_y = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2} \quad (5)$$

the measurement uncertainties of heat flux, heat transfer coefficient and the spray cooling efficiency are $\pm 1.5\%$, $\pm 8.5\%$ and $\pm 10.4\%$, respectively.

3. Results and discussions

3.1 Surface temperature distribution

Fig. 6 shows the surface temperature distributions of five piezoelectric atomizers. The experimental conditions of each atomizer such as heat flux, volumetric flow rate and spray height are marked in the figure. At first, for a certain atomizer (each sub-figure in Fig. 6), the minimum temperature appears at the center of heating surface. The local surface temperature increases as the increase of surface radius which is different from the results of pressure swirl nozzles. As reported in reference [13], the highest temperature of pressure swirl nozzle appears at the center of heating surface. For comparison of different atomizers, the average temperatures in each sub-figure were held nearly the same and the temperature range of ordinate axis was the same. It is concluded that from atomizer 1# to 5#, as the micropore outlet diameter increases, the temperature distribution become more uniform.

As spray height and volumetric flow rate are very important influence factors in

spray cooling, the effects of spray height and volumetric flow rate on surface temperature were investigated. As shown in Fig. 6(a-e), for a certain atomizer, there exists an optimal spray height at which the lowest surface temperature is achieved. For different atomizers, the optimal spray height is different. From atomizer 1# to 5#, as the micropore outlet diameter increases, the optimal spray height increases from 15mm to 40mm. What more, for atomizers with larger outlet diameter, the influence of spray height on surface temperature is more unapparent. Fig. 6(f) shows the effect of volumetric flow rate on the surface temperature with 3# atomizer at the spray height of 30mm and heat flux of 100 W/cm^2 . It is concluded that the surface temperature decreases with the increase of volumetric flow rate for a certain atomizer. The results of other four atomizers are similar with this one, so the figures are not shown here.

In order to clearly understand the effect mechanism of micropore outlet diameter on surface temperature, some typical spray atomization pictures of the five atomizers are shown in Fig. 7. By observation it is found that the spray field can be divided into two regions: dense spray region in the center and dilute spray region at the exterior. For 1# atomizer (micropore outlet diameter of $5 \mu\text{m}$), the spray is extremely dilute because the flow rate is as low as 0.5 mL/min and the droplets diameters are too small (the diameter of droplets is proportional to the micropore diameter [19]). For 2# atomizer (micropore outlet diameter of $7 \mu\text{m}$), the spray is denser than 1# atomizer but still dilute with a low flow rate of 1.0 mL/min . For 3# atomizer (micropore outlet diameter of $9 \mu\text{m}$), the spray is dense and fine, and the spray could last a longer distance from the atomizer outlet than the former two atomizers. This is possibly because the droplet velocity increases with the increase of micropore outlet diameter as reported in reference [32]. What's more, the flow rate of 3# atomizer is adjustable with a range from 3.8 mL/min to 5.0 mL/min . For 4# and 5# atomizers (micropore outlet diameter of $20 \mu\text{m}$ and $25 \mu\text{m}$), the spray pattern becomes a more uniform cylindrical spray which is different from the above cone spray, and the flow rate

ranges of them are 11.0-16.0 mL/min and 20.0-29.0 mL/min respectively. So the above temperature distribution results can be explained by the spray characteristics. At first, the spray is dense in the center and dilute at the exterior, so the temperature is low in the center and increases as the surface radius increases. As the micropore diameter increases, the flow rate increases and the spray becomes denser, as a consequence, the surface temperature decreases. When the micropore diameter exceeds 20 μm , the spray becomes a more uniform cylindrical spray, so the temperature distribution becomes more uniform.

3.2 Heat flux and heat transfer coefficient

Fig. 8(a-e) shows the effect of spray height on heat flux curve of five piezoelectric atomizers. For a certain atomizer, it can be found that the heat flux increases with the increase of surface temperature. Moreover, the heat flux increase becomes more sharply when surface temperature exceeds a certain value which means the onset of nucleate boiling. For each atomizer, there exists an optimal spray height at which the highest heat flux is achieved. For different atomizers, the optimal spray height is different which is the same with section 3.1. From atomizer 1# to 5#, as the micropore outlet diameter increases, the effect of spray height on heat flux becomes more and more unapparent. The effect of spray height can be explained by the spray area as explained in reference [33]. As shown in Fig. 7, the spray patterns of disk #1, #2 and #3 are full cone, so the spray areas of them increase with the increase of spray height. When the spray area is small, only a small fraction of the heating surface is directly impacted by the spray droplets, resulting in a low heat flux. With the increase of spray height, the heat flux increases at first and then decreases when the spray area is greater than the heating surface area and a fraction of spray droplets are wasted. However, the spray patterns of #4 and #5 atomizers are almost cylinder, so the spray areas are almost independent of spray height and hence the effect of spray height on heat flux is tiny.

Fig. 8(f) shows the effect of micropore outlet diameter on heat flux curves of five

atomizers in one figure. From atomizer 1# to 5#, the highest heat flux achieved in our experiment were 12.5 W/cm², 25.5 W/cm², 123.8 W/cm², 166.2 W/cm² and 170.2 W/cm², respectively. It is concluded that as the micropore outlet diameter increases, the heat flux increases. This is because the flow rate increases with the increase of micropore diameter. The greatest heat flux increment (98.3 W/cm²) occurs between diameter of 7 μm and 9 μm. When micropore outlet diameter exceeds 9 μm, the heat flux increment become smaller and smaller (42.4 W/cm² between 9 μm and 20 μm; 4.0 W/cm² between 20 μm and 25 μm). This indicates that the heat flux enhancement with the increase of micropore outlet diameter is more sensitive when the micropore is smaller than 9 μm.

Fig. 9(a-c) show the effect of volumetric flow rate on heat flux curve of three piezoelectric atomizers (3#, 4# and 5#). For a certain atomizer, it is evident that the heat flux increases with the increase of flow rate which means the optimal volumetric flow rate of a certain atomizer is the highest flow rate that the atomizer can obtain. Fig. 9(d) shows the effect of flow rate (range from 0.5 mL/min to 29 mL/min) on heat flux for all size of atomizers at a certain surface temperature. With the increase of volumetric flow rate, the heat flux increases quickly at first, and then increases slowly. This indicates that the heat transfer increase brought by the increase of flow rate decreases with the increase of flow rate. That is to say the further increase of flow rate could not bring much benefit.

Fig. 10 shows the heat transfer coefficient of five piezoelectric atomizers at their own optimal spray height and spray flow rate. It is found that with the increase of micropore outlet diameter, the corresponding heat transfer coefficient increases. The highest heat transfer coefficient of 2.0 W/(cm²K) was achieved with the micropore outlet diameter of 25 μm at flow rate of 29.0 mL/min.

In order to clearly understand the effect mechanism of micropore outlet diameter on heat flux, the water film behaviors of different atomizers were recorded by a camera. Fig. 11 shows some typical water film pictures of the five atomizers. Through

qualitative observation, it is found that the water film distribution is not uniform. The liquid film is thin in the center of the heating surface. With the increase of surface radius, the film thickness increases at first and then decreases. This is consistent with the non-uniformity of temperature distribution. With the increase of surface temperature, boiling bubbles occur in the water film. This explains the sharp increase of heat flux when surface temperature exceeds a certain value. The spray impact area (cavity in the center of water film) increases with the increase of micropore outlet diameter. With the increase of micropore outlet diameter, the film thickness become thinner at first, and then become thicker as the micropore outlet diameter exceeds $20\mu\text{m}$. This is because with the increase of the micropore outlet diameter, the impact velocity [32] and flow rate increase, so more film can be washed out by the inlet droplets. However, the further increase of flow rate lead to accumulation of water on the heating surface which makes the film thicker. So, the increment of heat flux decreases when the micropore outlet diameter exceeds $20\mu\text{m}$.

3.3 Spray cooling efficiency

Spray cooling efficiency is another important heat transfer parameter of spray cooling which expresses the utilization efficiency of working fluid. Fig. 12 shows the spray cooling efficiency of different piezoelectric atomizers. With the increase of surface temperature, the spray cooling efficiency increases slowly at first and then increases sharply when the surface temperature exceeded a certain value. The sharp increase of spray cooling efficiency is caused by the boiling heat transfer during which the latent heat utilization of water increases a lot. As the micropore outlet diameter increases, the flow rate increases and the spray cooling efficiency decreases. The highest spray cooling efficiency of 55.2% was achieved with the micropore outlet diameter of $5\mu\text{m}$ at flow rate of 0.5 mL/min. From atomizer 1# to 5# (micropore outlet diameter from $5\mu\text{m}$ to $25\mu\text{m}$), the highest spray cooling efficiency were 55.3%, 54.5%, 53.8% , 22.6% and 12.8%, respectively.

Fig. 13 shows the comparison of spray cooling efficiency and heat flux at the

same surface temperature of 100°C with volumetric flow rate range from 0.5 mL/min to 29.0 mL/min (different flow rate generated by five atomizers). It is found that taking all atomizers into account, the relationship between spray cooling efficiency/heat flux and flow rate could be generalized into one exponential decay/growth curve. The correlations between spray cooling efficiency (η)/ heat flux (q) and volumetric flow rate (Q) of all the atomizers can be generalized as Eq. 6, 7. The corresponding coefficient of determination R^2 values are also given in Eq. 6, 7. The R^2 values of them are relatively high which means the curves can fit the points very well and all size of atomizers are following the same rule.

$$\eta = 33.6\text{Exp}(-Q/12.4) + 4.5, \quad R^2 = 0.9829 \quad (6)$$

$$q = 127.3 - 55.9\text{Exp}(-Q/2.1) - 79.1\text{Exp}(-Q/16.8), \quad R^2 = 0.9980 \quad (7)$$

With the increase of volumetric flow rate, the spray cooling efficiency first decreased sharply and then decreased slowly which is contrast with the change of heat flux. This indicates that the heat flux enhancement caused by flow rate increase is at the expense of spray cooling efficiency decrease. Therefore, to achieve high heat flux as well as high spray cooling efficiency, there exists a optimal flow rate (a corresponding optimal micropore outlet diameter). Fortunately, as a compromise, the 3# atomizer (micropore outlet diameter of 9 μm) can achieve relatively high heat flux of 123.8 W/cm² at a low volumetric flow rate of 5.0 mL/min, and the corresponding spray cooling efficiency was as high as 53.8%. This is because of the excellent atomization performance of 3# atomizer as shown in Fig. 7 and the thinnest water film on the heating surface according to Fig. 11.

4. Conclusions

To optimize the heat transfer performance of piezoelectric atomizer based spray cooling, a piezoelectric atomizer was presented in this paper. The effects of micropore outlet diameter, spray flow rate and spray height on heat transfer performance as well as spray cooling efficiency were investigated. And the key findings can be summarized

as follows:

(1) Piezoelectric atomizer based spray cooling is an effective method for high heat flux removal at low flow rate. In this study, a maximum heat flux as high as 170.2 W/cm^2 with micropore diameter of $25 \text{ }\mu\text{m}$ was achieved.

(2) Taking flow rate of all atomizers into account, the relationship between spray cooling efficiency/heat flux and flow rate could be generalized into one exponential decay/growth curve which means all size of atomizers followed the same rule. With the increase of micropore outlet diameter, the spray flow rate and heat flux increased but the spray cooling efficiency decreased as a sacrifice. The optimal diameter of $9 \mu\text{m}$ 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% .

(3) For each atomizer, there exists an optimal spray height at which the maximum heat flux and minimum surface temperature can be achieved. The optimal spray height differed with the micropore outlet diameter and was mainly influenced by the atomization performance of the piezoelectric atomizer.

(4) For each atomizer, the heat flux increased with the increase of spray flow rate which means the optimal flow rate of a certain atomizer was the highest flow rate this atomizer can obtain.

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Figures and Tables

Fig.1 Schematic of piezoelectric atomizer used in this study

Fig.2 Microscope photographs of micropore disks with different outlet diameters

(a)5 μ m (b) 7 μ m (c) 9 μ m (d) 20 μ m (e)25 μ m (f) 30 μ m

Fig.3 Photograph of piezoelectric atomizer

Fig.4 (a) Photograph of piezoelectric atomizer based spray cooling system. (b)

Schematic diagram of spray cooling system.

Fig.5 Photograph of heating block and the thermocouples' arrangement

Fig.6 Surface temperature distribution of different piezoelectric atomizers

Fig.7 Atomization images of different piezoelectric atomizers

Fig.8 Heat flux curves of different piezoelectric atomizers at different spray height

Fig.9 Heat flux curves of different piezoelectric atomizers at different flow rate

Fig.10 Heat transfer coefficient for different piezoelectric atomizers

Fig.11 Water film behavior on the heating surface

Fig.12 Spray cooling efficiency for different piezoelectric atomizers

Fig.13 Comparison of Spray cooling efficiency and heat flux for different spray flow rates

Table 1 Micropore disk parameters of different piezoelectric atomizers

Micropore disk parameters		value				
Atomizer No.	1#	2#	3#	4#	5#	6#
Outlet diameter (μm)	5	7	9	20	25	30
Inlet diameter (μm)	105	110	108	150	155	160
Hole pitch (μm)	130	150	150	180	180	180
Volumetric flow rate (mL/min)	0.5	1.0	3.8~5.0	11.0~16.0	20.0~29.0	\