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Research paper

Experimental investigation of large area spray cooling with compact chamber in the non-boiling regime

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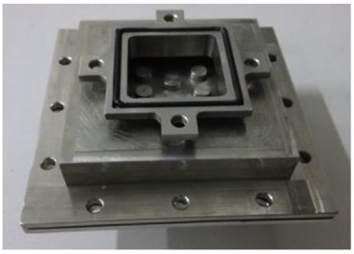
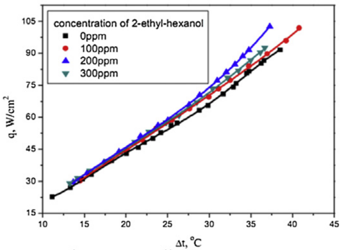
HIGHLIGHTS

- Temperature non-uniformity is expanded by increasing heat flux on large surface.
- Heat flux of 91.5 W/cm^2 is achieved in non-boiling regime with pure water.
- Heat transfer is enhanced by changing of flow rate or height with multi-nozzle.
- Heat transfer is increased by 15% with 200 ppm surfactant compared with pure water.

GRAPHICAL ABSTRACT



Multi-nozzle array and compact chamber



The spray cooling curves

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ABSTRACT

The development trend of spray cooling system is adapting to strict working conditions such as high heat flux, large heating surface and complex fluid management. Therefore, for the purpose of cooling large heating surface in a compact space, this paper designed a novel multi-nozzle array and set up a test rig of spray cooling loop. The spray characteristics of the nozzle were tested by Phase Doppler Anemometer system, and the effects of temperature uniformity, flow rate, spray height and surfactant of 2-ethyl-hexanol on heat transfer performance of the spray cooling system were studied. According to the spray cooling curves obtained, the heat flux on the heating surface (30 mm × 30 mm) can reach 102.6 W/cm^2 at least using surfactant and 91.5 W/cm^2 using pour water. The temperature non-uniformity was expanded with increasing heat flux. The results simultaneously indicate that the heat transfer performance is closely associated with volume flow rate and spray height, while the performance is improved by increasing volume flow rate and optimizing spray height. In addition, trace amounts of 2-ethyl-hexanol surfactant added into the working fluid can enhance the heat transfer performance of spray cooling which is increased by 15% with 200 ppm 2-ethyl-hexanol surfactant compared with water added nothing.

1. Introduction

With the increase of power density of electronic chips, radar, diode array and other equipment, heat accumulation leads to the high temperatures which reduce the life and stability of the device, and the conventional heat dissipation methods are difficult to reach

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Nomenclature

d_{32}	droplet sauter mean diameter, mm
H	spray height, m
t_f	inlet temperature of working fluid, °C
t_{surf}	heating surface temperature, °C
R	cross section radius, m
u	droplet axial velocity, m/s
Greek letters	
λ	heat conductivity, W/(m · K)
δ	distance of temperature layers
Subscripts	
surf	surface
f	fluid

the desired thermal control requirements. Compared with forced convection, pool boiling, jet impingement and etc, spray cooling is a rapid cooling method for high heat flux with significant advantages such as less flow rate demand, high heat dissipation capacity, low superheat degree and no contact thermal resistance with the heating surface [1–4]. The process of spray cooling can be described as below: high-pressure working fluid is atomized through a nozzle into tiny droplets, and liquid film is formed on the heating surface while the droplets impact on the surface continuously, then the heating surface is cooled by droplets impact, and liquid film convection, evaporation and boiling. Spray cooling heat transfer mechanisms are very complex because of superposition of multiple mechanisms. Some mathematical models were proposed and the spray cooling process were divided based on heat transfer modes [5], and numerous studies of spray cooling heat transfer mechanisms in detail were performed such as nucleate boiling [6], film convection [7] and film evaporation [8] and so on.

The influence factors of heat transfer performance in spray cooling are intricate and diversified, and plenty of experiments were performed for optimizing the relevant spray parameters. Cheng et al. [9,10] studied the impact of spray parameters on heat transfer such as inlet pressure, spray height, flow rate, spray angle with single rotating atomized nozzle in detail based on mathematical model and experiments. The results showed that these spray parameters affected on heat transfer by impacting on spray characteristics such as Sauter mean diameter, droplet velocity and droplet number density, and heat transfer performance was significantly improved by optimizing relevant spray parameters. Moreover, the heating surface temperature was considered non-uniform which was caused by the spray characteristics non-uniformity. Xie et al. [11] scrutinized the structure of spray cone based on two optical techniques and analyzed the heating surface temperature non-uniformity, and found that the spray cone and surface temperature affected the temperature non-uniformity. Zhang et al. [12] and Martínez-Galván et al. [13] analyzed the effect of surface roughness, Xie et al. [14] and Bostanci et al. [15] and Silk [16,17] designed a series of enhanced surfaces. Furthermore, other influence factors, for example, non-condensable gas [18] and microgravity [19] were also studied in the experiments.

In addition to the influence of the parameters, optimal design is also a way to improve heat transfer performance in cooling system. Hajmohammadi [20,21] designed and optimized several new patterns for the highly conductive pathways in conductive cooling, and found that peak temperature and volume occupied were significantly reduced. The optimization of heat flux elements in rectangular duct and fins in heat exchangers [22,23] in convective cooling were carried out, as well as optimized structure design in radiative cooling [24]. However, spray cooling as a complex heat transfer method including conduction, convection and radiation [5], corresponding structural optimization was very lacking. Lin [25] studied the affect of nozzle orientation, and Shedd and Pautsch [26,27] optimized the designed of nozzle array which did not achieve the final optimization. The constructal design of compact chamber and nozzle array including fluid management needed long-term studies in spray cooling system.

Water is widely used as working fluid in spray cooling system due to cheap price and convenient acquisition, and traces of soluble additives and surfactants are added in pure water for the purpose of improving heat transfer. Jia and Qiu [28] studied the sodium dodecyl sulfate additives in spray cooling, and considered that the additive resulted in relative small diameters and low superheat in nucleate boiling regime. Cheng et al. [29] experimented with heat transfer enhancement by adding high-alcohol surfactant (i.e., 1-octanol and 2-ethyl-hexanol) and dissolving salt additive (i.e., NaCl and Na_2SO_4). The enhancement factor curves showed that heat transfer was obviously enhanced with high-alcohol surfactant and salt additive, and the heat transfer of spray cooling increased by 36% for the addition of 150 ppm 2-ethyl-hexanol compared with that for pure water. Additives and surfactants were also used for metal quenching in transient spray cooling. Qiao [30] compared pure water and 100 ppm sodium dodecyl sulfate mixed solution as working fluid by cooling 240 °C hot surface, and found the heat transfer was enhanced 300% in nucleate boiling regime. Ravikumar et al. [31] made reference to the conclusion of Cheng et al. [22], while studied anionic surfactant (i.e., sodium dodecyl sulfate, SDS), cationic surfactant (i.e., cetyltrimethyl ammonium bromide, CTAB) and nonionic surfactant (i.e., polysorbate20, Tween20) in the works in detail. He considered that SDS-Tween20 binary mixture surfactant had the best performance due to high surface activity (low surface tension) and high wettability.

In fact, spray cooling has been applied in Cray X1/SV2 supercomputer [27] and spacecraft [19], and single nozzle has been replaced by multi-nozzle array in the device since multi-nozzle adapted to large and diverse heating surface. The studies of multi-nozzle in spray cooling have also been expanded. Pautsch and Shedd [26] experimented with a series of multi-nozzles to cool 70 mm × 70 mm heating surface with FC72, and obtained CHF (critical heat flux) with 77.8 W/cm^2 in the boiling regime. Tao and Huai [32] studied the heat transfer in non-boiling spray cooling with two nozzles and Tan et al. [33] and Hou et al. [34] designed similar multi-nozzles and investigated spray cooling with 10 mm × 20 mm and 16 mm × 32 mm heating transfer respectively. Based on a detailed visualization and heat transfer study, Shedd [27] proposed characteristics of nozzle for next generation spray cooling such as be scalable to large surface, maintain small package volume, etc.

In summary, numerous studies of spray cooling focused on mechanisms and influence factors of single nozzle system has been performed. However, limited works studied on heat transfer performance of multi-nozzle spray cooling with large heating surface, especially the impact of relevant parameters and heat transfer enhancement in a compact space. Consequently, in order to study multi-nozzle spray cooling with large heating surface, while preventing instability caused by the phase change in the compact space, this paper designed a novel multi-nozzle array, set up a closed loop spray cooling system, and investigated heat transfer performance of multi-nozzle spray cooling with 30 mm × 30 mm heating surface in the non-boiling regime. The spray characteristics of nozzle were tested in detail and relevant influence parameters such as working fluid flow rate and spray height were also analyzed