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Experimental investigation on heat transfer of spray cooling with the mixture of ethanol and water

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ABSTRACT

Experiments were conducted to investigate the performance of the spray cooling heat transfer. Pure water and the mixture of water and ethanol (the volume fraction of ethanol ranges from 0.05% to 10%) were used as working fluids. The performance of pure water and the mixture were compared using the identical heater and solid-cone spray nozzle. The maximum heat flux in the experiment was up to 170 W/cm^2. The experimental results indicated that adding ethanol to water is one of the most effective methods to enhance the heat dissipation and to control the device temperature simultaneously. The volume fraction of ethanol in water is the main factor affecting the spray cooling performance. The optimal volume fraction of ethanol for the improvement of the heat transfer performance is 4%.

1. Introduction

With the rapid increase of power density of the electronic components, more effective cooling technologies are necessary for enhancing the heat dissipation to ensure the equipment being under the temperature limit since high device temperature has negative impact on the lifetime and stability of the equipment. Compared with other cooling methods, spray cooling has the advantage of high heat dissipation capacity with low coolant mass flow rate [1]. By adopting spray cooling technology, electron devices show higher operation reliability with lower temperature [2].

The spray cooling process includes two regimes, i.e., the single-phase regime and the two-phase regime [1,3]. The heat flux of the single-phase regime is small without evident occurrence of phase change. As a result, the heat transfer performance is relatively poor. In the two-phase regime, the heat transfer performance is improved significantly, which results from the phase change of the working fluid [4,5]. In conclusion, the heat transfer performance in the two-phase regime is much better than that in the single-phase regime. Therefore, in order to improve the spray cooling performance, the two-phase regime should be utilized [6].

In a spray cooling system, the physical properties of the working fluid can considerably influence the cooling performance [7,8]. Generally, pure water [9], alcohols [10–12], fluorocarbon fluid [13], R134a [13–16], liquid ammonia and other refrigerating fluid [17] are used as the working fluid in spray cooling systems for different applications. Among these working fluids, water has an obvious advantage in heat transfer because of its distinctive physical properties. It is well known that the saturated temperature of water at atmospheric pressure is approximately 373 K. As a result, the temperature of the hot surface needs to be higher than that to keep the spray cooling in the two-phase regime. However, for most electronic chips, the surface temperature is usually below 350 K to ensure their normal safety operations [18,19].

In order to keep the surface temperature lower than the safety temperature and to improve the cooling performance, several methods were proposed. Some substitute medium instead of water was used in the previous studies, such as some refrigerating fluid [20], FC-72 [6], FC-87 [21] and iso-butane [22]. These refrigerating fluids [23] can keep the surface temperature lower than 373 K. However, since the specific heat, density and latent heat of the refrigerating fluid are much smaller than water, the cooling performance has a limitation in some instances.

Another method is reducing the chamber pressure to decrease the saturation temperature [24]. The reduction in the saturation temperature could trigger the two-phase regime at a low temperature, which improves the cooling performance and keeps the surface temperature below 373 K simultaneously. However, keeping a low pressure in the chamber makes the device more complicated.

Some other researchers proposed the idea to add the additive into water. Wang et al. [25] and Qiao et al. [8] added some soluble sodium

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Nomenclature

A	heater surface area [m^2]
c_{pl}	constant-pressure specific heat [kJ/kg·K]
d_{32}	Sauter mean diameter [μm]
h_{fg}	latent heat of vaporization [kJ/kg]
h	heat transfer coefficient [W/(cm^2·K)]
I	electric current [A]
k	heat conductivity [W/m·K]
$\dot{m}$	mass flux on the heater [m^3/m^2·s]
N	droplet number flux [1/s]
P	pressure [MPa]
Q	mass flow rate [m^3/s]
q	heat flux [W/cm^2]
T	temperature [K]
U	voltage drop [V]
u	velocity [m/s]
We	Weber number [−]
x	distance [mm]

Greek symbols

δ	uncertainty
ρ	density [kg/m^3]
ν	kinematic viscosity [m^2/s]
σ	surface tension [N/m]
α	spray angle [deg]
η	heat loss rate [%]

Subscripts

in	inlet
w	heater surface

dodecyl sulfate at different concentrations to pure water. Compared with pure water, the heat transfer was improved dramatically in the two-phase regime by adding a small amount of sodium dodecyl sulfate. At the same time, the inception temperature of the two-phase regime was also reduced. Cheng et al. [11] experimentally studied the heat transfer characteristics with addition of high-alcohol surfactant and dissolving salt additive. Results showed that the alcohol surfactant and soluble salts additive can effectively enhance the heat transfer performance in the spray cooling. However, the solution with soluble salts additive may corrode the pipeline and equipment of the cooling system, which prevents it from further practical applications.

Lin et al. [26] investigated the heat transfer performance with the mixture of water and methanol. The volume fractions of methanol as an additive are 20%, 50% and 100% in his research [26]. The results demonstrated that with the addition of methanol, the surface temperature was lower than that with pure water. However, the cooling efficiency of the mixture was also lower than pure water.

Ethanol is an ideal additive in the practical application of electronics cooling due to its low saturated temperature, low freezing temperature, high solubility in water, environmental friendliness and good compatibility with many materials. Chen [27] studied the spray cooling performance using ethanol, water and their 50/50 binary mixture by volume. The results showed that the best working fluid to enhance the spray cooling performance is water, then the binary mixture, and ethanol is the worst. Karpov et al. [28] experimentally studied the heat transfer with pulsed spray rather than continuous spray onto a vertical surface using ethanol aqueous solution in a concentration range of 0–96%. The maximum heat transfer coefficient was achieved at an ethanol concentration within 50–60%.

In conclusion, previous research verified that the additive in water could enhance heat transfer for a spray cooling system. However, several studies also indicated that the mixture with additive has disadvantage over the heat transfer performance. The main reason might be the different volume fraction of additive used in the experiment. In other words, the volume fraction of additive is very important for the cooling performance.

In this paper, the spray cooling performance is investigated experimentally, and ethanol is used as an additive in water as the working

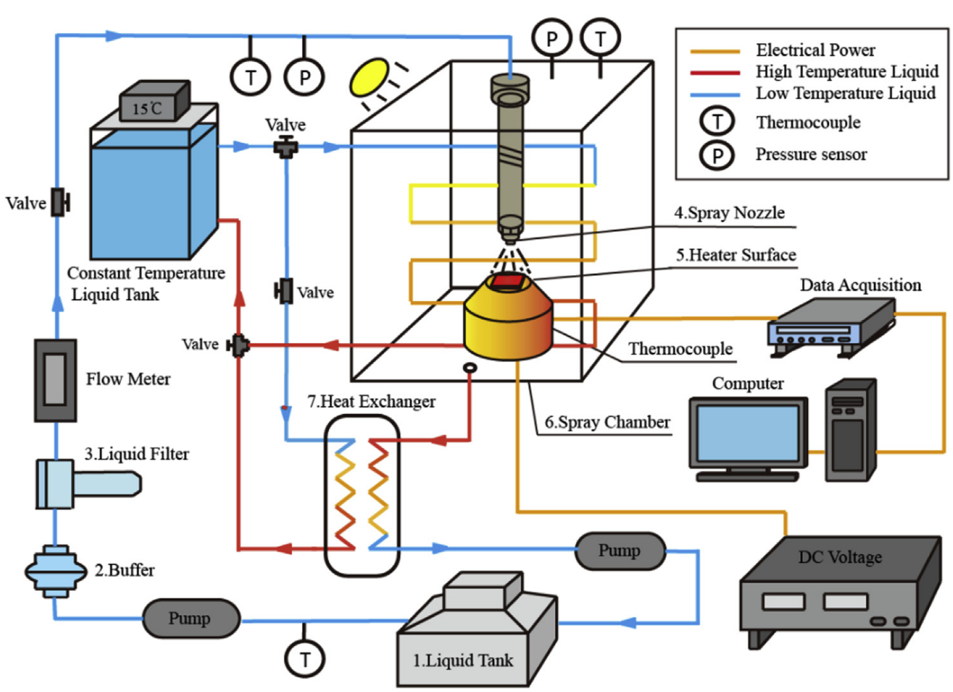

Fig. 1. Schematic of the spray cooling system.