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The effects of micro-structured surfaces on multi-nozzle spray cooling

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HIGHLIGHTS

- The optimal micro-structured surfaces were straight fins2 and 3 in zone I.
- The heat transfer performance of cubic pin fins was the best one in zone II.
- A dimensionless number was proposed to scale heat transfer enhancement.
- Temperature uniformity was discussed.

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ABSTRACT

Experiments were conducted to investigate heat transfer characteristics of spray cooling with eight nozzles for micro-structured surfaces included cubic pin fins and straight pin fins of different sizes. Liquid volume flow rate ranged from 2.46×10^{-2} $m^3/s/m^2$ to 3.91×10^{-2} $m^3/s/m^2$ and the corresponded inlet pressures changed from 0.28 MPa to 0.6 MPa by keeping the inlet water temperature between 20.4 °C and 24.31 °C. And the input power of heat block varied from 180 W to 1080 W. The results show that the heat transfer performances of straight fins2 and straight fins3 are the best in single phase zone, but the cubic pin fins is better in two phase zone. Notably, the critical point between single phase zone and two phase zone shifts to left with the increasing of liquid volume flow rate. Moreover, with the liquid volume flow rate increasing, the heat transfer coefficient increases as well, but straight fins1 and polished surface are not sensitive to this change. For a deeper analysis of the heat transfer enhancement, a dimensionless number (DM) is created to characterize heat transfer performance of different micro-structures in single phase heat transfer. We verified the dimensionless number using experimental results in this study and previous literature. Furthermore, the micro-structured surfaces have negligible effects on temperature distribution except for cubic pin fins.

1. Introduction

Among alternative solutions for cooling high-powered devices, spray cooling has the advantages of removing high heat flux and providing uniform temperature distribution in a confined space. Traditionally, spray cooling was utilized to cool highly heated surfaces for equipments and processes in metallurgy, chemical and nuclear industry [1,2]. Recently, it has received increasing attentions in the development of modern technologies, such as the cooling of electronic devices and high power solid-state lasers. It has been reported that spray cooling had been applied in the cooling of Cray X1 vector supercomputers [3].

However, the maximum CHF was limited to 1000 W/cm^2. In order to obtain higher heat flux and more uniform temperature, multi-nozzle spray cooling has been widely studied. The heat transfer performance of multiple nozzle sprays significantly depends on geometry and spacing [3,4]. Lin et al. [5,6] carried out an experimental investigation with eight miniature nozzles at spray pressure drops greater than 1.72 bar. It showed that the CHF levels with eight-nozzle sprays were 90 W/cm^2 with pure FC-72 and 490 W/cm^2 with pure methanol respectively. Y. B. Tan et al. [7] developed a correlation based on their multi-nozzle spray cooling experimental results to predict the dimensionless heat flux. Jia and Qiu [8] made an experiment to investigate the advantage of surfactant addition in spray cooling with five nozzle arrays and indicated that the surfactant addition could result in a relatively constant heat removal rate near the CHF regime. Panao et al. [9] presented a thermal assessment of a multi-jet strategy for spray cooling system. The assessment considered a diverse number of

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Nomenclature

A	area of micro-structured surface, m^2
A_0	area of polished surface, m^2
a	the height of each fin, μm
Bo	Bond number
b	the groove width, μm
c	the fin width, μm
d	normal distance between the two rows of thermocouples, m
DM	a dimensionless number
g	gravitational constant, m/s^2
h	total heat transfer coefficient of heated surface, W/m^2/K
k	conductivity of the heat block, W/m/K
l	normal distance between the heated surface and the upper row of thermocouples, m
Nu	the averaged Nusselt number in natural convection
Pr	the Prandtl number
q'	averaged heat flux of the heated surface, W/m^2
Q'_{loss}	the heat transferred to surrounding air from the part of heat block between two rows of thermocouples, W
Q_v	inlet volume flow rate, m^3/s
Ra$_L$	the Rayleigh number
T_{lower}	averaged temperature of the lower row of thermocouples, °C
T_{upper}	averaged temperature of the upper row of thermocouples, °C
T_w	the averaged temperature of the heated surface, °C
T_l	temperature of inlet water, °C
T_c	averaged vapor temperature in spray chamber, °C
Greek symbols	
γ	surface tension of water, N/m
δ_k	error in conductivity, W/m/K
$\delta_{q'}$	the uncertainty of the averaged heat flux, W/m^2
δ_T	error in temperature measurement, °C
δ_{T_w}	the uncertainty of the averaged temperature, °C
δ_x	error in thermocouple location, m
ε_T	heat loss percentage between two rows of thermocouples
ρ	density, kg/m^3
Subscripts	
V	vapor phase
l	water phase

nozzles. Their results supported that the multi-nozzle spray cooling was a good choice for smaller processors with more adequate thermal management system. However multi-nozzle spray cooling cannot meet the increasing cooling requirements, so more effective methods are required.

Recently researchers have been paying more attentions to the enhanced surfaces that show great potential to further improve the performances of spray cooling heat transfer. Various studies have been reported. Sehmbey et al. [10] discovered that increasing the surface roughness had a positive effect on heat transfer through a spray cooling experiment with liquid nitrogen. Pais et al. [11] studied the surface roughness and its effect on the heat transfer mechanism in spray cooling using an air atomizing nozzle. They found that the nucleate boiling played a major role in the heat transfer when the surface roughness was greater than 1 μm. However, for films of the order of 0.1 μm, heat was conducted through the film and evaporated on the surface, yielding very high heat fluxes of the order of 1200 W/cm^2 at very low superheat. Kim et al. [12] built the microporous structures on the heated surfaces and studied the effect of particle size on the heat transfer coefficients experimentally using the air-atomized nozzle. The results showed that the heat transfer coefficient increased by up to 400% relative to that of uncoated surface cooled by dry air, and this enhancement was maintained at high heat fluxes. They attributed this enhancement to the increased capillary forces between microstructures.

Bostanci et al. [13] conducted the experiments to investigate spray cooling on micro-structured surface with ammonia using two vapor atomized spray nozzles, and a smooth surface was also tested for comparison. Results suggested that the heat transfer coefficients increased by 112% and 49% for treated surfaces with protrusions and indentations respectively, in comparison with smooth surface, when the heat flux over heated surface was 500 W/m^2. Stephan et al. [14] studied the spray cooling heat transfer performance on micro-structured surfaces consisted of micro pyramids with different heights. They found that a significant enhancement in the heat transfer performance due to the surface structures could be observed, especially at low coolant fluxes. The authors attributed this to the increase of the three phase contact line, which leads to more effective thin film evaporation. Bostanci et al. [15] had studied spray cooling with ammonia on structured surfaces to determine the CHF limits. The results showed that the maximum heat flux of multi-scale structured surface increased by 18% over smooth surface, up to 910 W/cm^2 at nominal flow rate. And the multi-scale structured surface with pyramidal fins and protrusions achieved the highest CHF value of 1090 W/cm^2, so did the surface with protrusions. de Souza et al. [16] conducted an experiment to study the spray cooling on copper-foam enhanced surface with R134a. The enhancement factor of copper-foam surface is as high as 1.39. In sum, treated surfaces can enhance heat transfer significantly. It is essential to understand the heat transfer mechanism to obtain the optimized micro-structure, however, few studies were found.

Chien et al. [17] investigated multi-nozzle jets cooling with FC-72 on cubic pin fins and straight pin fins. They indicated that the heat transfer performance increased with the increasing of liquid volume flow rate or surface area enhancement ratio. Their data shows that the heat transfer performance of two-phase jets is dependent on Re, Bo and surface enhancement ratio. Hsieh et al. [18] investigated evaporative heat transfer characteristics of a water droplet spray on the plain and square micro-studs silicon surfaces at very low spray mass fluxes up to 4.41 mL/cm^2. They indicated that the Bond number of the microstructures was an important factor to explain the heat transfer enhancement of evaporative spray cooling on micro-structured silicon surfaces. Moita et al. [19] studied the impact of droplets onto micro-structured surfaces and scaled the effects of surface topography on secondary atomization. They indicated that wetting properties were responsible for different characteristics of the thermal-induced atomization. The results also show good correlation between the mean sizes of the secondary droplets generated by thermal-induce atomization and the ratio of the mean height of the peaks and the pitch between them.

As above mentioned, the surface technologies improve heat transfer performance greatly. However the enhancement mechanisms of treated surface are not clear yet. Besides, previous studies on micro-structured surface enhancing multiple nozzle spray cooling and influencing temperature uniformity are limited. The main objective of the current work is to investigate the effects of