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Research Paper

Integrated thermal control and system assessment in plug-chip spray cooling enclosure

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HIGHLIGHTS

- A novel multi-heat source plug-chip spray cooling enclosure was designed.
- Enhanced surfaces with different geometric were analyzed in integrated enclosure.
- Overall thermal control with adjustable parameters in enclosure was studied.
- Temperature disequilibrium of multi-heat source in enclosure was tested.
- A comprehensive assessment system used to evaluate the practicality was proposed.

GRAPHICAL ABSTRACT

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ABSTRACT

Practical and integrated spray cooling system is urgently needed for the cooling of high-performance electronic chips due to the growth requirements of thermal management in workstation. The integration of multi heat sources and the management of integral system are particularly lacking. In order to fill the vacancies in the study of plug-chip spray cooling, an integrated cooling enclosure was designed in this paper. Multi heat sources were placed in sealed space and the heat was removed by spray. The printed circuit board plug-ins and radio frequency resistors were used as analog motherboards and chips, respectively. The enhanced surfaces with four different geometries and the plain surface were studied under the conditions of different inclination angles. The results were compared and the maximum critical heat flux (CHF) was obtained. Moreover, with the intention of the overall management of multi-heat source in integrated enclosure, the effect of the flow rate and the temperature disequilibrium, and the pulse heating in the process of transient cooling were also analyzed. In addition, a comprehensive assessment system, used to evaluate the practicality of spray cooling experimental devices, was proposed and the performance of enclosure was evaluated.

1. Introduction

With the rapid miniaturization and integration of electronic components and the ensuing increase in power density, conventional heat dissipation methods for electronic components are inadequate to meet the desired thermal control requirements. As an effective cooling method for high heat flux removal, spray cooling has been widely studied in recent years due to the tremendous potential compared with the conventional methods. In fact, the maximum cooling capacity with 1200 W/cm^2 has been achieved in the laboratory [1]. However, as an important mode of

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Nomenclature

t	thickness of fins, mm
t_d	gap of fins, mm
L	height of fins, mm
L_d	height of mixing fins, mm
B	thickness of fin base, mm
w	width of fins, mm
N	number of fins
A_w	surface area, m^2
q''	heat flux, W/m^2
h	heat transfer coefficient, $W/(m^2 \cdot K)$
T_w	surface temperature
T_{in}	inlet temperature, °C
T_{sat}	saturation temperature, °C
ΔT_{sub}	degree of subcooling, °C
Q''	volumetric flow rate per unit area, $m^3/(s \cdot m^2)$
c_p	specific heat of liquid, J/(kg·K)
h_{fg}	latent heat of vaporization, J/kg
d_0	diameter of nozzle orifice, mm
d_{32}	sauter mean diameter, mm
We_{d_0}	Weber number based on orifice flow conditions
Re_{d_0}	Reynolds number based on orifice flow conditions

Greek letters

α	spray inclination angle, °
ρ_f	density of liquid, kg/m^3
ρ_g	density of vapor, kg/m^3
σ	surface tension, N/m
μ_f	viscosity of liquid, Pa/s

Subscripts

f	liquid
g	vapor
sat	saturation
sub	subcooling

spray cooling, the plug-chip spray cooling enclosure with horizontal spray is lack of research at present, and most of the studies focused on the conventional component spray cooling system with single nozzle or multi-nozzle array theoretically and experimentally. The mode has a plurality of characteristics including integration, compactness, high efficiency and centralized control, and is mainly used in thermal management of integrated device with multi heat sources.

Optimization and enhancement of heat transfer are important goals for thermal management in spray cooling system especially in the novel mode. Spray inclination angle, the inclination of spray cone axis relative to the heating surface normal, is a controllable factor in conventional spray cooling. Previous investigations of spray inclination angle have typically emphasized the horizontally disposed heating surface and top-down spray cone. Visaria and Mudawar [2,3] conducted a systematic experiment study about the impact of inclination angles and found that the inclination angles had no noticeable effect on heat transfer in single-phase regime or two-phase regime, while critical heat flux showed a downward trend as the inclination angle increased. It was considered that the key reason of performance degradation was the reduction of volumetric flux delivered to the heating surface at greater angles. Silk [4] studied the enhanced surfaces and inclination angles of spray cooling with PF5060, and believed that the heat flux was enhanced because of appropriate film drainage from the surface, although the volume flux on the heating surface decreased with the increase of inclination angle.

Besides, the enhanced surface is another controllable factor to improve heat transfer performance in the conventional spray cooling system. The enhancement of surface could be divided into macro and micro enhancement. A series of studies on macro-enhanced surface were developed by Silk et al. [4,5]. These different surface geometries such as straight fins, cubic pin fins, pyramids, dimples, radial fins, porous tunnels and various combinations of the above geometries were designed in the experiments, with all experimental data compared with the results of flat surface under the same test conditions. The results showed that thin straight fins had more obvious heat transfer enhancement than thick fins, and cubic pin fins width and fin spacing had significant impact on heat transfer while fin height did not impact. Moreover, the detailed parameters of cubic pin fins, porous tunnels and so on were optimized experimentally. Silk thought that more nucleation sites, larger contact area and longer contact time with liquid were the main reasons for heat transfer enhancement with surface geometry. Hou et al. [6] studied different surface geometries in multi-nozzle spray cooling system. Surface geometrical scale and temperature uniformity were optimized and a dimensionless number used to scale heat transfer enhancement was proposed. Bostanci et al. [7] and Xie et al. [8] studied a variety of enhanced surfaces involving micro scale, macro scale and multi-scale structures that combine macro and micro scale surface. Similar conclusions were obtained that the multi-scale structured surface could achieve higher heat transfer performance than the single surface and the plain surface. Other forms of enhanced surfaces such as nano-structured surfaces [9] and microporous [10] were analyzed in detail as well as the relevant parameters. Numerous studies have been carried out on the impact of enhanced surface on heat transfer in spray cooling, and the results showed that improving surface characteristics was a convenient and efficient way to enhance heat transfer performance which benefits from outstanding fluid management, longer liquid residence time, increased nucleation sites and extended evaporation area. In addition, the capillary action was considered to play a significant role in the heat transfer on micro scale surface.

In addition, other optimization methods, such as replacement of working fluid [11–13] and enhancement of heat transfer based on surfactant and nanoparticles [14,15], focused on practical issues in spray cooling system. Moreover, in the thermal control of electronic device, the spray system faced more stringent requirements due to the compact space and high heat flux. The multi-nozzle with great scalability and versatility and the compact spray chamber were designed [7,12,16]. The relevant parameters including spray characteristics, spray height, flow rate, temperature uniformity, etc. were studied in the corresponding systems with single heating source.

The studies on influence factors and compact system of conventional spray cooling are adequate at present, while the plug-chip spray cooling system suitable for thermal management of multi-heat source in workstation and supercomputer has not been included in public journals yet. Therefore, a novel spray cooling mode called plug-chip spray cooling enclosure is proposed in the paper. Considering the component package, parts maintenance and device integration, the PCB (printed circuit board) plug-ins array is inserted vertically in a narrow space and the spray cone