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Spray cooling and flash evaporation cooling: The current development and application

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ABSTRACT

With the increasing power density of electronic chips, large radar, laser diode array and other equipments, the conventional heat dissipation methods are difficult to achieve the desired thermal control requirements increasingly. Spray cooling has attracted widespread attention due to its advantages in high heat flux removal such as less flow rate demand, high heat dissipation capacity, low superheat degree, no temperature overshoot and no contact thermal resistance with the heating surface. As of today, lots of researchers engage in this field and numerous achievements of spray cooling are obtained theoretically and experimentally. In this paper, an overview with spray cooling was completed. The current research progresses of heat transfer mechanisms of spray cooling in the three stages (single-phase regime, two-phase regime and critical heat flux regime) were summarized, and the influence factors, spray characteristics, heating surface characteristics, fluid characteristics and external environment characteristics, were analyzed in detail. The flash evaporation cooling, a special form of spray cooling, was also explored by a number of studies due to its irreplaceable advantage in low pressure environment or in space. Film flash evaporation and droplet flash evaporation significantly improve the cooling capacity of system and utilization of working fluid. In fact, the application of flash evaporation cooling is profound for development and expansion of spray cooling. Additionally, spray cooling system and nozzle were also elaborated in the paper.

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1. Introduction

With the rapid miniaturization and integration of electronic components and the ensuing increase in power density, conventional heat dissipation methods, such as forced convection, pool boiling, heat pipe, jet impingement, are difficult to meet the desired thermal control requirements gradually. Heat accumulation leads to higher operating temperature which has negative impact on lifetime and stability of equipments. Therefore, heat dissipation becomes the bottleneck of development for high heat flux equipments. Spray cooling, a high heat flux removal method, has won widespread attention at present. Compared with forced convection, heat pipe, jet impingement cooling and other conventional heat dissipation methods, spray cooling has numerous advantages such as less flow rate demand, high heat dissipation capacity, low superheat, no temperature overshoot and no contact thermal resistance with the heating surface [1–7]. Electron devices showed higher operation reliability with lower temperature after using spray cooling technology. Compared with air cooling, spray cooling could reduce 33 °C die (junction) temperatures as well as 35% power consumption [8]. The real die reliability testing (AMD Opteron) is completed in the laboratory, however, the wide application prospect of spray cooling in high heat flux removal is unquestionable. Several typical heat transfer methods and heat transfer coefficients are shown in Fig. 1 [2]. The advantage of spray cooling with high heat transfer coefficient had been visually manifested. At present, spray cooling has been applied in Cray X1/SV2 supercomputer and spacecraft successfully [7–10]. Moreover, space cooling has become the preferred solution in thermal control of diode array, large radar, laser transmitter, etc.

The process of spray cooling can be depicted as below: high-pressure liquid are atomized through the spray nozzle into fine droplets in a gaseous environment, and thin liquid film formed on the heating surface as the high-speed droplets impact on the surface continuously, then the heating surface was cooled by droplets impact, liquid film convection, evaporation and boiling. Spray cooling heat transfer mechanisms are extremely complex due to the combined effect of various heat transfer mode and the numerous coupling influence factors, and a large number of meaningful conclusions are obtained. However, the convincing and consistent conclusion of heat transfer mechanism suitable for various spray cooling system is not obtained currently.

Flash evaporation cooling is an advanced spray cooling technique in evaporation mode in the low pressure environment. When the environment pressure is lower than saturation pressure of liquid working fluid, the surface of liquid film and flying droplets occurs evaporation quickly and large amounts of heat is removed by liquid film and droplets. Compared with common spray cooling, flash evaporation cooling shows a more rapid and intense heat transfer. The flash evaporation cooling technology has been applied in spacecraft because of vacuum environment in the space [11–13], and flash evaporation cooling system with higher heat transfer efficiency and stability as well as more compacted structure is developing.

In this paper, we discussed the current research progress of spray cooling in detail by summarizing numerous studies, analyzed the complex heat transfer mechanisms of spray cooling and numerous factors of heat transfer performance, and introduced the issues and challenges in the application of spray cooling and flash evaporation cooling. We hope that the researchers have a comprehensive understanding of spray cooling from the paper.

2. Heat transfer mechanisms of spray cooling

The typical spray cooling curve contains three stages which are divided by the heat transfer mode on the heating surface: single-phase regime, two-phase regime and critical heat flux (CHF) (as shown in Fig. 2 [7]). When the heating surface is subcooling, the heat flux is small and increases with surface temperature slowly. The heat transfer performance is weak and the phase change hardly occurs until spray cooling goes into two-phase regime. In two-phase regime, an increase in the slope of the spray cooling curve indicates that heat transfer performance is improved significantly. As the surface temperature continues to rise, CHF will be achieved when heat flux reaches peak and no longer increases. The heat transfer performance in single-phase regime is worse than that in two-phase regime evidently, however, spray cooling in single-phase regime shows a higher stability due to no intense change of volume and pressure caused by phase change of working fluid. Therefore, according to their own characteristics, spray cooling in single-phase regime and two-phase regime can be used in different occasions.

Experimental methods are mainly used to research on spray cooling because of the extremely complex heat transfer mechanisms. Superposition of several heat transfer mechanisms and interaction between the various related parameters have brought enormous difficulties to researchers, however, relevant studies are still being expanded. Grissom et al. [14] divided spray cooling process into three modes: flooded mode, dry-wall mode and Leidenfrost mode. Jia [15] experimented with multi-nozzle based on the modified dry-wall mode. Expulsion rate ε, the ratio of outgoing to incoming droplets mass fluxes, was defined in the experiments. Heat transfer process of spray cooling was divided into four stages based on heat fluxes and expulsion rate. The stages arranged from low temperatures to high ones as follow: convective cooling regime, boiling in liquid film regime, droplets impinge cooling regime and CHF regime. Spray cooling heat transfer mechanism in single-phase regime and two-phase regime were quite different as well as the dominate modes in heat transfer [16]. We introduced two mechanisms separately in Sections 2.1 and 2.2.

2.1. Heat transfer mechanisms in the single-phase regime

Spray cooling heat transfer is dominated by single-phase regime at low heating surface temperature or high subcooling. In this stage, the system performs with limited heat dissipation capability, high operation stability and uniform distribution of heat dissipation flux. This heat transfer mode is favored in fragile electronic components and the unstable structure. In order to identify major associated parameters, researchers tend to establish heat transfer model and verify it experimentally.

Pautsch and Shedd [17,18] proposed a heat transfer model of spray cooling in single-phase regime, and divided the process into two or three parts: a single-phase part in and around the droplet impinge region, a boiling part in the corners away from the impinge region, and a single-phase drainage among several spray