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Progress of aerospace-based spray cooling applications

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Introduction

The heat flux generated by electronic components increases dramatically since the integration and miniaturization of electronic components have been extensively proposed (Chen et al., 2021; Teng et al., 2022). Huge generated amounts of heat and the decrease of heat dissipation area lead to the sharp increase in heat flux of the devices (Wang et al., 2015; Wang et al., 2022a). In some specific applications such as air-borne high energy-density directional weapons, the heat flux of electronic devices has been achieved at 10^3 W/cm^2 (Wang et al., 2021a). Thermal management becomes a key bottleneck in technology development because the service life, reliability, and stability of electronic devices are affected by the overheating caused by untimely dissipation of heat flux (Chen et al., 2022). Traditional single-phase cooling can no longer satisfy the demand of current heat dissipation, while the phase change process can absorb large amounts of heat (Hao et al., 2022), such as microchannel cooling (Zhang et al., 2021), jet impingement (Overholt et al., 2005) and spray cooling (Wang et al., 2017), which are now considered as highly-efficient methods that can take away a large amount of heat. Spray cooling is considered to have the advantages of large specific surface area, small coolant flow rate, small temperature difference between surface area and working medium, and high heat flux removal ability comparing other cooling methods (Wang et al., 2018c). Therefore, spray cooling technology has always been a hot technology in the field of electronic cooling, especially in the aerospace field with high heat dissipation requirements such as diode array, large radar, laser transmitter, and satellite electronics (Wang J. X. et al., 2016) as shown in Figure 1A,B. Thus, the operating principles, the influence factors, and prospects for aerospace-oriented spray cooling research have been reviewed in this paper.

The operating principles of spray cooling

The operating principle of spray cooling is a technology in which the coolant is atomized into small droplets to dissipate heat on the hot surface when passing through the high-pressure nozzle as shown in Figure 1C (Wang J. et al., 2021). According to the different temperatures of the heated wall, the domain heat transfer mechanism of spray cooling is different (Zhao et al., 2010). When the surface temperature is under boiling point, a thin liquid film is formed on the wall due to the continuous impact of droplets, and forced convection in the liquid film plays an important role in heat transfer. Pautsch and Shedd. (2006) used a non-intrusive total-internal-reflection-based optical technique and fundamental equations of geometric optics to measure the film thickness and found that the thickest film area has poor heat transfer, and the liquid film far away from the spray area will evaporate and dry quickly, resulting in heat transfer deterioration. When the temperature of the hot surface exceeds the boiling point of the coolant, phase change will happen inside the liquid film, and the dominant mode of heat transfer mechanism of spray cooling turns to nuclear boiling (Qiu et al., 2017). Nuclear boiling of spray cooling is similar to pool boiling in that the gasification core is first generated on the hot wall, then bubbles are formed and gradually separated from the surface. However, it is worth noting that the droplet impact of spray cooling cause liquid film internal disturbance to accelerate the bubbles escaping velocity, resulting in the higher spray cooling heat transfer efficiency. In addition, secondary nucleation is also the reason for the high heat transfer efficiency of spray cooling (Selvam et al., 2009), which is considered that a large amount of vaporization core is brought into the liquid film when the droplet impacts the liquid film, thus enhancing the heat transfer. When the temperature of the wall continues to rise, the bubbles generated cannot escape the wall in time and form a vapor film on the wall to prevent the new coolant from cooling the wall, which means that the cooling state has reached the critical heat flux (CHF) (Hou et al., 2013). The occurrence of CHF is an important reason to limit the development of spray cooling.

Influence factors in the aerospace field

Gravity and vibratory effect

In the aerospace field, spray cooling is often used in high-altitude airspace or space environments where the operating environment of spray cooling is rather different from that of near-ground applications. Thus, the influence of the gravity field must be considered (Sinha-Ray et al., 2014; Sinha-Ray and Yarin, 2014). The influence of gravity on heat flux under different flow rates and nozzle heights was experimentally discussed (Zhang et al., 2016). The results showed that increasing gravity loads improved heat flux in most cases, but had little effect at high flow rates and low nozzle height. A two-dimensional model was developed to study the temperature of a flat heated surface under different loads and the researchers found that the temperature of the wall surface under high overload was lower than that under normal gravity when the droplet velocity is 4 m/s (Pang et al., 2017). At present, the effect of gravity on spray cooling is still very vague, which leads to inconsistent conclusions from different studies. In addition to a lack of theoretical knowledge, the duration of an artificial space gravity environment (such as a falling tower, or parabolic flight) is relatively short (only a few seconds), which brings great uncertainty to its research (Wang et al., 2020). Another consideration in the aerospace field is the vibration field, a two-dimensional VOF model was utilized

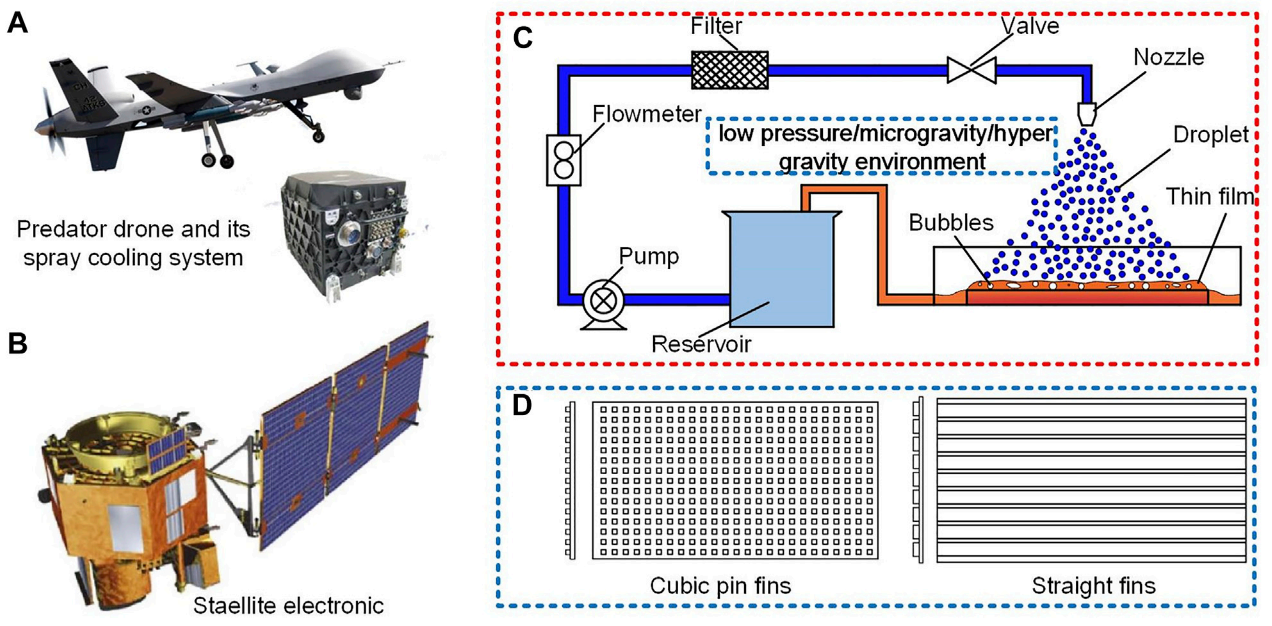

FIGURE 1
(A) and **(B)** application of spray cooling in aerospace field (Liang and Mudawar, 2017); **(C)** the principle diagram of spray cooling system; **(D)** enhanced heat transfer surface structures.

to study the influence of wall vibration conditions on heat transfer (Wang Z. et al., 2016). The results showed that high frequency and high amplitude would weaken heat transfer in the case of light droplet impact, while vibration would enhance heat transfer in the case of dense droplet impact. Currently, it is still a hot research area to explore the effect of vibration on spray cooling.

Low-pressure environment effect

Low environmental pressure is another influencing factor in high-altitude flight, which leads to the decrease of the saturation temperature of the working medium, facilitating a superheated state of the coolant after leaving the nozzle (Wang et al., 2018b). This will produce two instantaneous evaporation states: (1) the instantaneous evaporation/boiling of the droplet; (2) flash/boiling of the film covering the target surface (Cheng et al., 2015). The first phenomenon occurs when the droplet leaves the nozzle and is called the secondary breakup process due to the formation of bubbles inside the droplet (Wang et al., 2020). There are two main driving forces for secondary breakup process generation in droplet instantaneous evaporation/boiling process: (1) the initial temperature difference of the droplet (Chen et al., 2018); (2) bubbles produced in the droplet (Zeng and Lee, 2001). The second phenomenon occurs in the saturated film which can absorb lots of heat by using the latent heat of coolant. Based on the influence of environmental pressure on spray cooling, a one-dimensional mathematical model of liquid nitrogen flash spray cooling for thermal control of electronic equipment cabin of the near-space vehicle was proposed (Wang C. et al., 2018), where the ambient pressure was maintained below 5,530 Pa. The optimal operating conditions were determined, which is instructive for practical application.

Enhancement of spray cooling in the aerospace field

There are four main ways to increase the heat transfer effect of spray cooling: (1) exert external multi-physics physic fields; (2) promote larger area of heat transfer; (3) enhance coolant thermal properties. Shahriari et al. (2016) found the Leidenfrost effect can be limited and film boiling can be suppressed by adding an external electric field, which can increase the bubble escape rate and thus, enhance heat transfer. Sapit et al. (2019) used a fine nozzle to obtain a higher discharge rate of the sprayed coolant, creating a larger heat transfer area and attaining an enhanced heat transfer. Besides, surface treatment is one of the commonly used method to increase heat transfer area (Zhang et al., 2015). Finned surfaces (Rao, 2018), nano-/micro-structured surfaces (Hou et al., 2014; Oh et al., 2018), and porous-material-assisted functional surfaces (Jun et al., 2016) have been proven to enhance heat transfer, which all increased the contact area between coolant and heated surface as shown in Figure 1D. Liu et al. (2018) added millimeter-scale geometric structures (square fin, triangular fin, and straight groove fin) to the smooth surface and found that all three mm-scale microstructures can increase the heat flux of spray cooling, with the straight groove fin having the best effect, followed by square fin and triangular fin. Enhancing coolant thermal properties is another method to enhance heat transfer, such as nano-fluid (Riazi et al., 2016), saline solution (Cui et al., 2003), surfactant (Hsieh et al., 2015), which change the physical properties of the initial working medium, such as latent heat, thermal conductivity, surface tension, contact angle, etc. Most recently, Wang et al. (2018b) found that an immersed spray cooling could obtain an enhanced heat transfer because of the sufficient coolant supply and strong disturbance effect.

Perspectives of spray cooling in the aerospace field

Compared with the spray cooling technology on the ground, there are fewer publications in the aerospace field, mainly due to the difficult experimental conditions and high experimental cost. The United States Air Force Research Laboratory began to study spray cooling systems after it was proposed in the aerospace thermal management field in 2008 (Silk et al., 2008). Zhang et al. (2015) concluded that the spray cooling system with an ejector condenser was a promising prototype that intelligently collects and circulates coolant by effectively transporting two-phase flow through the ejector in a complex gravitational field in China. The research of airborne spray cooling systems is the key to the sustained and reliable operation of airborne technology in complex space or high-altitude air environments. Much more attention should be paid to it. In addition, how to adjust the flow of the working medium according to the thermal load so that the temperature of electronic components can be controlled within the range need to be explored in the future. At the present, a machine learning (ML) algorithm has been successfully applied in the spray cooling field (Wang et al., 2019). Machine learning mainly uses the training dataset to train the neural network model where the pattern of the focused spray cooling system can be learnt. Researches showed that machine learning can provide accurate prediction for complex thermal-fluid system due to high reliability. Wang et al. (2019) used a backpropagation neural network method to predict the thermal performance both in flash-boiling and subcooled regions with six parameters input and the error of ±7% was observed. Moreover, a transient thermal performance prediction was also developed using ML (Wang et al., 2021b) which paves the way for ML-based temperature control of spray cooling as computational capabilities have been sufficiently developed (Wang et al., 2022b; Cao et al., 2022).

Conclusion

This paper introduces the heat transfer mechanism of spray cooling, its unique influencing factors, and challenges in the aerospace field, and also describes the methods to strengthen the heat transfer. Gravity field, vibratory field, and lower pressure were considered as the influencing factors. However, there is still no completely convincing conclusion about the influence of gravity on spray cooling. How to obtain accurate experimental data is still a key problem to solve. This paper aims to provide a further understanding of spray cooling in the aerospace field for readers and promote the application of spray cooling in the aerospace field.

Author contributions

SW contributed to conception of the study. XC wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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