Applications of Spray Cooling Technology in Aerospace Field

Ran Liu, Lei Zhang and Xian Zhang
Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China
liuran_cast511@126.com

Abstract. Spray cooling is an effective heat transfer technology that uses liquid atomization and boiling to take away the heat from the surface of a cooled object. It has the characteristics of large heat transfer coefficient, good temperature uniformity, small degree of superheat, high critical flux and small circulation flow. It has become a research hotspot of efficient heat and mass transfer technology. The electronic components in the aerospace field are generally in the harsh environment of high heat flux density, high vacuum, microgravity and high radiation. With the increasing use of high-power components in spacecraft, the heat dissipation of spacecraft has become the first problem to be solved in spacecraft design. In response to this problem, the author has studied a large number of spray cooling technologies for aerospace applications, and has certain application value for the research of heat dissipation of high heat flux components in aerospace field.

1. Introduction
With the improvement of satellite functions, the development of the space industry and the continuous development of deep space exploration, the compact design of the spacecraft and the miniaturized design concept enable the integration of numerous electronic components in smaller and smaller areas. The heat flux density of electronic devices has increased dramatically. Coupled with the harsh environment of high-vacuum, micro-gravity and super-radiation, the spacecraft's heat dissipation problem has become the first problem to be solved in spacecraft design.

Spray cooling technology is a phase change cooling technique that uses atomized droplets to be sprayed onto a heat exchange surface to remove heat through phase change evaporation of the medium. Its characteristics are: high heat transfer coefficient, good temperature uniformity, low superheat, high critical heat flux density and small circulation flow, which is the most competitive high heat flux density thermal control technology. At present, NASA has listed closed spray cooling circuit system technology as one of the research priorities of future thermal control systems. The US Navy and the Department of Energy have set up special funds for the research of spray technology in the past ten years, and successfully achieved the heat dissipation target of heat flux density of nearly 1000W/cm² [1-2]. In recent years, ACT has successfully realized the commercialization of atmospheric gravity spray technology[3]. Domestic research on spray cooling technology has also been carried out in many aspects and has achieved certain results.

2. Spacecraft thermal control system
In order to apply the spray cooling technology to the spacecraft thermal control system, relevant research under microgravity conditions should be carried out. A large number of experimental studies have been carried out in the United States to study the heat transfer effect of spray cooling by using
aircraft parabolic flight or free fall to simulate the microgravity environment. NASA and the US Air Force have conducted a lot of research on the effects of spray cooling and heat transfer under microgravity by providing historical flight data, falling towers, gravity-reduction flight tests and laboratories, and many achievements [4-10]. In NASA's CEV (Crew Exploration Vehicle) project, the heat dissipation of the spacecraft thermal control system usually adopts the evaporative cooling method of heat sink sublimation to take away heat. The spray cooling can achieve high heat dissipation under relatively low working fluid flow, which is applied to flash evaporator. The open spray cooling system has been tested and verified [11-13].

The use of water as a flash evaporator working fluid takes away excess heat from the spacecraft, and the vaporized water is directly discharged into space. This type of flash evaporator is called compact flash evaporator. The spray flash evaporator developed by NASA is a cylindrical heat exchanger. The surface of the heat exchanger is covered with fins to enhance the heat transfer during spray cooling. Figure 1 shows the spray nozzle array of the flash evaporator, and Figure 2 shows the simulation calculation model for the liquid flowing through the flash evaporator.

![Figure 1. Spray nozzle array of flash evaporator](image1)

![Figure 2. Simulation calculation model for liquid flowing through flash evaporator](image2)

To simulate the spray cooling effect in a vacuum environment in space, NASA tested a single nozzle in a vacuum chamber with a vacuum of $10^{-3}$ torr [13], as shown in Figure 3. Test proved that the compact flash evaporator system with open spray cooling is lighter and more compact than the current heat sink sublimation system, and is more suitable for future spacecraft needs. The original intention of this project was to develop open spray cooling technology, but the closed spray cooling system also carried out a lot of research for the thermal control of future space missions.

![Figure 3. A single nozzle is tested in a vacuum chamber](image3)

Many ground test studies have been carried out on closed spray cooling technology at domestic and foreign. Schematic diagram of spray cooling closed loop system is shown in Figure 4. The system
includes micro pumps, spray nozzles, spray chamber, condensers, heaters, etc. The micro pump provides drive power to the system. The liquid comes out of the pump port, passes through the heater to adjust the temperature and then enters the spray chamber. The liquid is atomized and sprayed on the heat source through the nozzle. Two-phase flow returns to the condenser to cool to a liquid state, completing a cycle.

**Figure 4.** Schematic diagram of spray cooling closed loop system

NASA’s Glenn Research Center conducted a flight test on spray cooling. The KC-135 microgravity test bed was used for flight test to verify and study its operation ability, heat transfer performance and characteristics under microgravity conditions. FC-72 is used as the working fluid [14]. China Academy of space technology also developed a prototype of the spray cooling system with an ultimate heat flux density exceeding 300 W/cm² [15]. However, the closed spray cooling system is still only in the experimental research, and it is not really applied to the spacecraft thermal control system.

### 3. High power laser cooling system

In the past decade, high-power diode lasers have developed rapidly. Laser-diode arrays (LDAs) technology can be applied to Mars satellites, earth science, and Mercury exploration. However, the heat generated by LDAs is very high, which requires a thermal control method with high heat dissipation capability, and spray cooling is currently the hottest research focus.

In 2003, Universal Energy researched spray cooling technology for high-power semiconductor laser arrays with funding from the US Air Force Laboratory [16]. The device has eight nozzle arrays with a closed system, the nozzle is 8.8mm away from the hot surface, the spray chamber size is 28.5mm (length) × 17.0mm (width) × 8.8mm (height), and the working medium includes FC-87, FC-72, methanol and water, the power of the circulatory system is provided by a micro pump. Prototype of laser spray cooling is shown in Figure 5. The super-cooled liquid is sprayed through the nozzle on the hot surface, and most of the droplets form a thin liquid film on the hot surface, and a small portion of the droplets evaporate to remove heat. The steam leaves the spray chamber together with the liquid, enters the condenser through the two-phase flow passage and re-condenses into liquid, participating in the next stage of the cycle.
4. Thermal Protection systems for Hypersonic Vehicle
Thermal protection in ultra-high temperature areas is a key issue for hypersonic vehicles. NASA proposed a solution for the design of a liquid spray cooling thermal protection system, as shown in Figure 6[17]. The liquid spray cooling thermal protection system uses a sandwich structure. The skin material is directly heated, using a corrugated sheet as the core element of the sandwich structure and secured to the heated skin side. Spray tubes are installed inside the corrugated sheet as a passage for the coolant. Each of spray tubes is provided on one surface thereof with rows of closely spaced holes. The coolant is sprayed from the hole to the heated area, the coolant is heated to a gaseous state, and the gas is discharged to the adjacent side by the passage on the side wall of the corrugated sheet. Inside the corrugated sheet, the pipe is used for exhausting the gas. During operation, the temperature of the spray cooled sheet is the same as the coolant evaporation temperature. For large-area cooling, the system's cooling capacity is 57kW/m²; for a small area of 5cm², the system's cooling capacity can reach 230kW/m², and the internal structure temperature can be maintained at 330K.

Figure 5. Prototype of laser spray cooling

Figure 6. Liquid jet cooling thermal protection system
In China, Liu Shuang\cite{18} proposed a new method for applying spray cooling to metal thermal protection systems for the head cone and wing leading edge of hypersonic vehicles. Designed and manufactured a sample of metal thermal protection system using spray cooling, built an oxyacetylene experimental platform, and tested the overall performance of the spray cooling thermal protection system sample. Test results show that the spray cooling can dissipate 800-1000 kW/m$^2$ of heat.

5. **Liquid nitrogen spray chamber in space environment simulation equipment**

In the current space cryogenic environment simulation in the aerospace field, the main method of using liquid nitrogen is to adopt a structure of a liquid nitrogen coil and a heat exchanger. However, when the ambient temperature outside the satellite changes significantly with time, a dynamic orbital thermal environment simulation is required. At this time, a variable temperature gas nitrogen system is required to change the heat sink temperature. One of them is the heat sink temperature control system with a liquid nitrogen spray chamber, as shown in Figure 7.

![Figure 7. Thermal shroud temperature control system with liquid nitrogen spray chamber](image)

The liquid nitrogen spray chamber adopts the spray cooling technology, which uses a low temperature liquid nitrogen nozzle to atomize liquid nitrogen into fine droplets, directly contacts the heat exchange with the circulating cold nitrogen, and uses the latent heat of liquid nitrogen to achieve cooling, by adjusting the supply of nitrogen and liquid nitrogen. The pressure changes the flow rate of liquid nitrogen to achieve dynamic and precise adjustment of the outlet nitrogen temperature, which can control the inlet temperature of the heat sink to ±1 °C. Moreover, after liquid nitrogen atomization, the total surface area of the liquid is significantly increased by the continuous liquid breaking into a large number of discrete droplets, and the contact area with the environment is remarkably improved, and the heat and mass transfer efficiency is greatly increased, thereby reducing the consumption of liquid nitrogen.

The vacuum thermal test equipment \cite{19} produced by American PDM Company is equipped with a gas-nitrogen temperature-regulating heat sink, which can adjust the heat sink temperature within the range of 117-394 K, the temperature rise and fall rate can reach 1.1 K/min, and the system can withstand the heat load of 50kW. The external process of gas-nitrogen temperature regulation and heat sinking adopts a one-way closed cycle, and nitrogen gas is supplied by two vaporizers, each of which can generate 1870 m$^3$/h of nitrogen gas for 8 hours. Nitrogen is regulated by six high-density vaporization units and then fed into the heat sink to control the nitrogen flow and temperature by controlling the output of the vaporization unit.

In 2013, Turkey built a space environment simulation equipment with a gas-nitrogen temperature control system \cite{20}, and the gas-nitrogen temperature control unit used a liquid nitrogen shower. The
liquid nitrogen flows out of the storage tank through the vaporizer and is vaporized into nitrogen. The nitrogen gas passes through the turbo compressor and the regenerative heat exchanger, enters the liquid nitrogen spray chamber, and is thoroughly mixed with the liquid nitrogen, and the heater power after the shower is adjusted. Nitrogen is obtained at a temperature of -165 °C to +110 °C and enters the heat sink.

In 2016, Beijing Institute of Spacecraft Environment Engineering successfully developed a gas-nitrogen temperature control system using liquid nitrogen spray cooling. The surface temperature range of the heat sink surface is -170.0°C~+150.0°C, and the temperature rise and fall rate reaches 3.5°C/Min, heat sink uniformity is better than ±3.0 °C.

6. Conclusion
In spacecraft environmental testing, spray cooling has been widely used in engineering applications, and it is easier to implement engineering applications on the ground than the difficulty of using spray cooling in space environments. The use of spacecraft, especially the closed-loop spray cooling technology, is still in the laboratory stage and is not widely used. In addition to the lag of theoretical research, the control method of controlling the temperature of the cooled object reduces the volume and weight of the test prototype, which is also the direction for future research on spacecraft.

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