

Review

Spray Cooling as a High-Efficient Thermal Management Solution: A Review

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Abstract: As one of the most promising thermal management solutions, spray cooling has the advantages of high heat-transfer coefficient and maintaining a low temperature of the cooling surface. By summarizing the influential factors and practical applications of spray cooling, the current challenges and bottlenecks were indicated so as to prompt its potential applications in the future. Firstly, this paper reviewed the heat-transfer mechanism of spray cooling and found that spray cooling is more advantageous for heat dissipation in high-power electronic devices by comparing it with other cooling techniques. Secondly, the latest experimental studies on spray cooling were reviewed in detail, especially the effects of spray parameters, types of working fluid, surface modification, and environmental parameters on the performance of cooling system. Afterwards, the configuration and design of the spray cooling system, as well as its applications in the actual industry (data centers, hybrid electric vehicles, and so on) were enumerated and summarized. Finally, the scientific challenges and technical bottlenecks encountered in the theoretical research and industrial application of spray cooling technology were discussed, and the direction of future efforts were reasonably speculated.

Keywords: spray cooling; thermal management; cooling performance; industrial applications



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1. Introduction

Electronic chips are the most important components to support the development of technology including the Internet, artificial intelligence, and supercomputers, etc. To pursue high performance and high integration, the power density of electronic chips must increase dramatically, yielding much higher heat-dissipation requirements. If heat cannot be removed in time, a local hotspot with a large temperature gradient will directly affect the performance and operational reliability of the equipment. Recent studies [1] have indicated that about 55% of electronic equipment failure is related to high temperatures. Meanwhile, once the temperature exceeds 75 °C, the failure rate of chips exhibits an exponential increase [2]. Therefore, long-time stable and reliable operation of high-performance chips requires a high-efficiency thermal management strategy to remove high-heat flux and maintain a device's temperature below its limits.

Today, electronic chips can produce heat fluxes as high as 10–100 W/cm² [3]. In next-generation electronic systems, the typical heat flux can even exceed 1000 W/cm² [4,5]. However, the cooling capacity of the conventional heat-dissipation methods (air cooling, microchannel, semiconductor cooling, and heat pipes, etc.) has been demonstrated to be less than 100 W/cm² [6,7], which cannot meet the increasingly stringent chip-cooling requirements. One solution to the aforementioned cooling dilemma is the spray-cooling technique, owing to its advantages such as high heat removal capability with a small

amount of working fluid consumption, precise temperature control, and relatively good temperature homogeneity. For instance, spray cooling using water as a working fluid has demonstrated a strong ability to remove heat fluxes as high as 1000 W/cm^2 [8,9]. Thus, spray cooling has been considered as a desirable cooling strategy for high-power electronic devices and has been intensively discussed in recent years.

In spray-cooling systems, the liquid working medium is rapidly atomized into small droplets through the nozzle, which impinges and accumulates on the targeted cooling surface to form a liquid film. Single-phase or two-phase heat transfer occurs to dissipate heat by both sensible and latent heat. In the single-phase regime, it is widely accepted that forced convection caused by droplet impingement and film flow is the dominant mechanism. By contrast, spray-cooling heat transfer in two-phase regimes is extremely complicated since forced convection, liquid film evaporation, surface nucleation, and secondary nucleation are all involved, and there is still no convincing consensus formed so far on the spray-cooling heat-transfer mechanisms.

To sum up, this work aimed to introduce the state of spray cooling for the heat dissipation of electronics by reviewing the available experimental studies and summarizing the direction of future development. The paper is structured as follows. Firstly, the incomparable advantages of spray-cooling technology in thermal management of electronic equipment in comparison with other cooling technologies are displayed, and the complex heat-transfer mechanism of spray cooling is briefly investigated. Secondly, influencing factors of cooling performance are explored and analyzed in detail, including spray characteristics, surface modification, properties of the working medium, and system and environmental parameters, etc. Afterwards, the structural design and configurations of spray-cooling systems and their applications in practical industry are listed and summarized. Finally, the scientific challenges and technical bottlenecks of spray-cooling technology in theoretical research and industrial applications are discussed, and the main research directions in the future are reasonably predicted. We hope that researchers can better understand spray cooling via this paper and provide guidance for promoting the industrial applications of spray cooling.

2. Heat-Transfer Mechanism and Influence Factors of Spray Cooling

Assisted by the boiling curve and/or temperature–time cooling curve, the heat-transfer response of a surface associated with spray cooling can be quantified [10]. Based on the heat-transfer mode on a spray-covered hot surface, the typical boiling curve for spray cooling can be classified into three regimes (stages): the single-phase regime, the two-phase regime, and critical heat flux (CHF), as illustrated in Figure 1. The first stage is the single-phase regime, in which the phase change hardly occurs in the liquid film owing to the low superheat. The heat flux is small and increases with surface temperature slowly. Thenceforth, with the increase of surface temperature, spray cooling would enter the nuclear boiling regime. In this two-phase regime, the slope of the boiling curve becomes steep and the cooling performance is significantly improved. As the surface temperature continues to rise to reach a specific critical value, bubble nucleation will be replaced by localized vapor blankets. At this moment, surface heat flux reaches the peak (CHF) and no longer increases. Beyond this limit, the deterioration of heat transfer and overheating occur, which may damage the electronic equipment.

It is worth noting that this work focused on spray cooling for the thermal management of high-power electrical devices, which means the temperature of the heated surface is within the low-temperature region. The heat-transfer behavior in this region occurs before the CHF. This indicates that CHF is the maximum heat-transfer capacity in the low-temperature region, which is an important index to evaluate the ultimate cooling capacity of spray cooling and guide the practical application of spray cooling. In this sense, numerous researchers have been devoted to exploring the heat-transfer mechanism and CHF of spray-cooling systems at various conditions. Apart from CHF, the heat-transfer coefficient (HTC) and spray-cooling efficiency are also crucial criteria to evaluate the performance of spray cooling. HTC is defined as the heat-transfer rate per unit area per Kelvin of wall

superheat, which determines the equipment temperature of a given heat load [6,11]. The cooling efficiency, η , to present liquid utilization rate, can be described as the ratio of the actual heat flux to the theoretical maximum heat flux that can be removed by the supplied coolant [12,13].

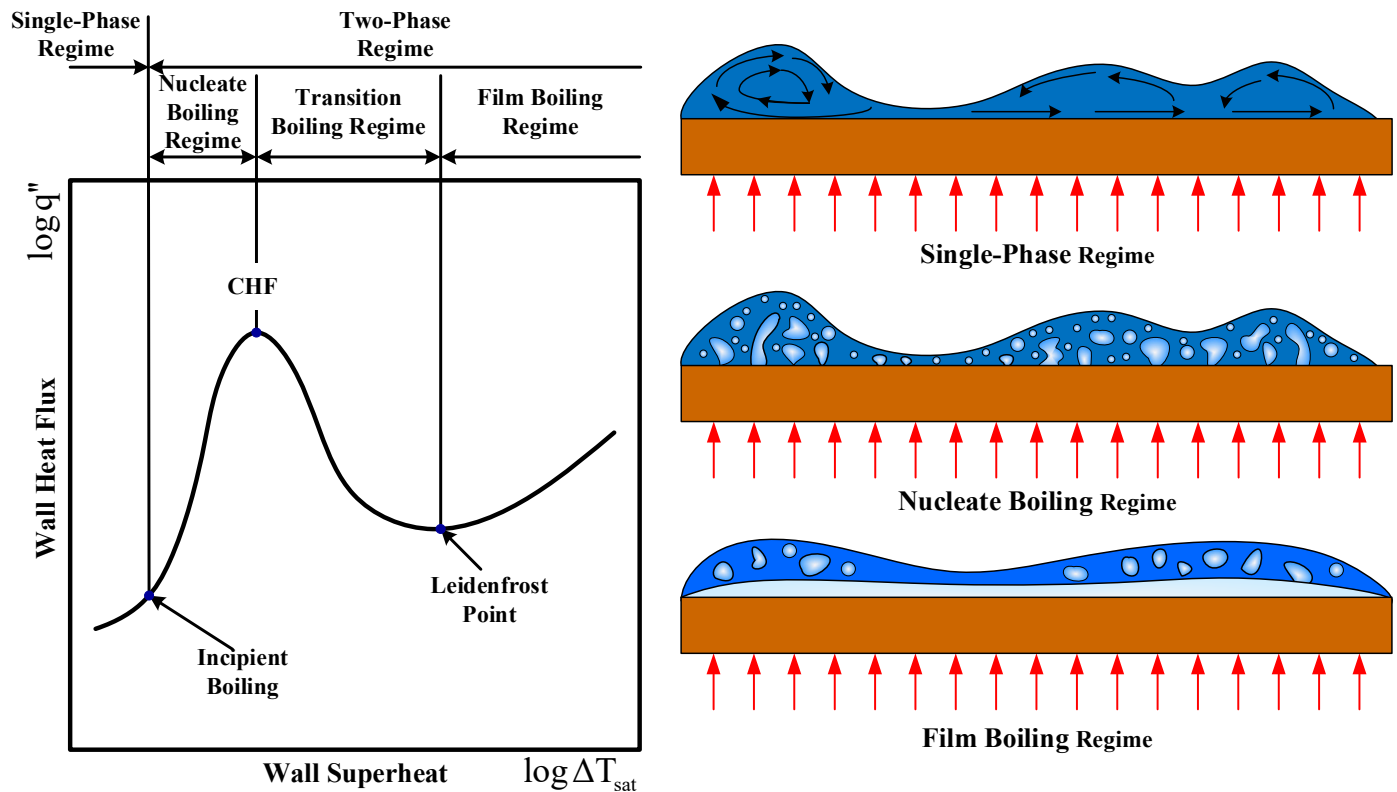


Figure 1. Typical boiling curve (modified and adapted from Mascarenhas and Mudawar) [10].

There are many factors that affect the heat-transfer mechanism of spray cooling, and the effects of these factors are not independent. Hence, this paper analyzed the influence of the key factors on spray cooling from four aspects: spray parameters, properties of the working medium, surface modification, and system and environmental parameters.

2.1. Influence of Spray Parameters on Heat-Transfer Performance

Spray parameters, such as flow rate of the working fluid, nozzle type, nozzle-to-surface distance, pressure in the spray chamber, and so on, must have a significant effect on the size, impact velocity, temperature, and spatial distribution of liquid droplets formed after atomization, changing the dynamics and thermodynamics of spray droplets and finally affecting the heat transfer between the liquid film and the hot surface [14,15]. Therefore, the spray parameters are the most important determinants of the heat-transfer performance of spray cooling.

2.1.1. Nozzle Type

There exist a large variety of nozzles, which directly determine the atomization characteristics and post-atomization spray behavior. The pressure-atomizing nozzles are the most widely applied in spray cooling, which can be classified into gas-assisted nozzles, pressure swirl nozzles, and straight-tube nozzles. Researchers have adopted a different view of the

impact of the atomizer-type nozzles on spray cooling. Hsieh and Tsai [14] studied the CHF of spray cooling using different types of nozzles. The results revealed that nozzle diameter has no perceptible effect on the CHF, whereas it can strongly affect the utilization of working fluid. Employing R134a as the working fluid, Martínez-Galván et al. [16] obtained similar spray parameters as well as similar heat-transfer performance and film thickness with different internal geometries of atomizing nozzles, which is consistent with the observation of Hsieh and Tsai [14]. Nevertheless, Rashad et al. [17] obtained different results for the effect of geometric configurations of the pressure-swirl atomizers on the spray cone angle, Sauter mean diameter (SMD), and other spray characteristics. It was shown that an appropriate geometric ratio of the atomizer can enhance the atomization, while a large increase may lead to more frictional losses and poor atomization. At present, straight-tube nozzles are commonly used in cryogen spray cooling (CSC). Zhou et al. [18,19] designed a cylindrical expansion chambered nozzle for CSC applications in laser dermatology, yielding a more concentrated spray and better cooling efficiency than those achieved using a straight-tube nozzle.

2.1.2. Flow Rate

The published literature reveals that flow rate is the most influential factor on the performance of spray cooling [20,21], while its mechanism has not been fully revealed. Estes and Mudawar [22] found that high flow rate reduced the cooling efficiency and an obvious transition between single- and two-phase heat transfer was not observed, i.e., high flow rate is not necessarily beneficial to spray cooling. Nevertheless, the increase of flow rate has positive effects on the surface heat flux, but the cooling efficiency consequently decreases [13,20,23–25]. At low flow rates, few droplets impact the hot surface, and thinner liquid film will promote evaporation and ultimately lead to a high cooling efficiency. At high flow rates, however, more spray droplets impact the target surface and a thicker liquid film will reduce the evaporation rate of the liquid film. Furthermore, thicker liquid film is easier to be washed off the cooling surface without sufficient heat transfer. Therefore, the cooling efficiency decreases with the increase of flow rate. In the vacuum-flashing spray-cooling systems, Cheng et al. [26] and Fu et al. [27] claimed that the increase of flow rate can enhance heat transfer because of the increase of droplet velocity and the scouring of liquid film on the surface. Nevertheless, Cheng et al. [28] showed that surface temperature non-uniformity becomes more pronounced with the increase of flow rate. As a result, there is an optimal spray flow rate value to balance the heat transfer and the consumption of working fluid [29].

For the pressure-atomizing nozzles, increasing the spray flow rate is usually achieved by the improvement of the inlet pressure, which affects the cooling performance of spray in at least two aspects: velocity and particle size of the droplet. On the one hand, increasing the inlet pressure helps to accelerate the working fluid, which strengthens the impingement of the droplet on the liquid film, and finally enhances the droplet–wall convection heat transfer [30,31]. On the other hand, higher inlet pressure results in the decrease of the droplet size, which contributes to liquid film evaporation [32]. At lower surface temperatures, increasing the nozzle inlet pressure can improve the uniformity of the heated surface temperature and attain a higher cooling rate [32]. However, droplet speeds as high as 50–60 m/s will lead to a higher temperature of the heating surface, since most droplets splash directly from the heating surface and the amount of liquid involved in heat transfer is reduced [33]. In any case, it is necessary to improve the energy efficiency and economic benefit of spray cooling through reasonable flow distribution and optimization strategies in the future.

2.1.3. Spray Distance and Spurt Duration

Spray distance (nozzle-to-surface distance) and spurt duration are the most easily adjusted parameters in spray-cooling systems. Aguilar et al. [34,35] conducted a series of experiments to investigate the influence of spray exit-to-target distance and spurt duration on the surface heat flux and temperature. It was found that the spray distance is more conducive to enhancing surface cooling than the spurt duration [36]. Up to now, there has been limited literature discussing the effects of spurt duration on spray-cooling performance. Tian et al. [37] investigated the effect of spurt duration on the transient cooling performance in an open-loop pulsed spray-cooling system, and found that the moderate spurt duration ($\Delta t = 30$ s) can provide relatively high cooling efficiency and a large surface temperature drop. Hsieh and Tsai [14] found that the spray distance has a significant effect on the CHF for a variety of nozzles. Furthermore, the smaller the spray distance, the higher the CHF. However, more recent research demonstrated that the best cooling capacity of spray cooling is achieved at an optimal nozzle-to-surface distance. Through a theoretical study, Tian et al. [38] determined that the optimal spray distances for R32, R404A, and R134a were 22.5, 43.1, and 66.0 mm, respectively. Some researchers believe that with regard to the effect of nozzle-to-surface distance, maximum CHF can be achieved when the spray completely covers the heat-exchange surface [25,39]. However, some others discovered that the optimal spray distance corresponding to the strongest heat dissipation capacity is smaller than that achieved when fully cover the heating surface [40]. The experimental research of Zhou et al. [41,42] showed that the determination of the optimal spray distance also needs to consider the spray-back pressure. Moreover, they revealed the coupling effect of spray distance and nozzle diameter on the surface heat-transfer performance of cryogen spray cooling [43]. Sarmadian et al. [44,45] observed the significant influence of spray distance on the CHF in presence of vibration, and this effect depended on the vibration range. The abovementioned results suggest that the spray distance is associated with spray coverage area, impinging energy and droplet flux. Due to the different experimental conditions, the most suitable nozzle-to-surface distances obtained from each experiment are incomparable. Thus, more in-depth research is still needed.

2.1.4. Spray Angle

When spray impinges on the surface vertically, liquid accumulated on the heating surface may hinder heat transfer. To increase the heat transfer in this zone, inclined spray can be used. Most related studies about spray angle (between the spray axis relative to the normal direction of the heating surface) have shown that the cooling performance gradually increases with the spray angle up and sharply decreases after attaining an optimum angle [46–49]. Compared with vertical spray, inclined spray reduces the area of the stagnation zone, which is beneficial to remove the excess liquid on the cooling surface and improve the heat-transfer ability [49,50]. However, some researchers believe that inclined spray could increase CHF, but results in the deterioration of the surface temperature non-uniformity [51]. Therefore, the enhancement effect of inclined spray on the spray-cooling performance is controversial.

2.2. Properties of the Working Fluid on Heat-Transfer Performance

2.2.1. Coolant Used in Spray Cooling

The importance of the physical properties of the working fluid on the heat transfer of spray cooling has been widely recognized [52,53]. The most widely used working fluids of spray cooling for the heat dissipation of electronics can be classified into two types: non-dielectric and dielectric liquids [54].

In most cases, non-dielectric liquids are aqueous coolants, for example, pure water [25], methanol [55], ethylene glycol (EG) water solution [56], n-Propanol-water [57], NaCl solution [58], propylene glycol [59], and ethanol–water solution [60], which exhibit high specific heat, high thermal conductivity, and low viscosity. Among these coolants, water has attracted widespread attention in spray cooling for electronics due to its distinct advantages such as low cost, non-flammability, being easily available, possessing a high latent heat of vaporization, and being pollution-free. The highest value of CHF for water spray cooling in the published literature depends upon spray systems and experimental conditions. For instance, the CHF value reached 500 W/cm^2 , which was reported by Lin and Ponnappan [55], 638 W/cm^2 by Mudawar and Valentine [61], and 945.7 W/cm^2 by Chen et al. [62]. Pais et al. [63] found that the maximum CHF could reach up to 1200 W/cm^2 by using an air–water atomizing nozzle. Nevertheless, due to the relatively high boiling point, heat transfer of water spray cooling in the practical application of electronics is in the single-phase cooling mode and the surface temperatures of electronics are all above 80°C [64]. Moreover, water cannot directly contact electronic devices because of its poor electrical insulation properties. A specialized cold plate is required for heat removal, which increases the complexity of the spray-cooling system, reduces the heat-transfer capacity, and limits its application in the thermal management of high-power electronics [65].

A high boiling point and superior physical characteristics make water the first choice for a single-phase coolant [66], and dielectric liquids are the first choice for two-phase boiling heat transfer [67]. Typical dielectric liquids include Aromatics, Silicones, Fluorocarbons, and Aliphatics-based fluids, characterized by low density, low boiling point, non-reactivity, non-corrosivity, as well as good chemical and thermal stability [54,68]. Lin and Ponnappan [55] obtained a CHF of spray cooling up to 90 W/cm^2 by fluorocarbon fluids (FC-87/FC-72) with a working temperature of 25°C . Visaria and Mudawar [69] achieved a high CHF of 349 W/cm^2 by FC-77 with a target surface temperature of 129.4°C . Hou et al. [70] established a closed-loop R22 (boiling point of -40.8°C at 1 atm) spray cooling system which can handle heat fluxes as high as 276.1 W/cm^2 with 26.8°C cooling surface temperature at the nozzle-inlet pressure of 0.8 MPa. Later, Chen et al. [71] compared the cooling performance of R134a (boiling point of -26.1°C at 1 atm) and R22. The maximum CHF of R134a spray reached 117.2 W/cm^2 with 46°C target surface temperature, while those of R22 were 276.1 W/cm^2 and 26.8°C target surface temperature, respectively. The result demonstrated the heat-transfer characteristics of R22 spray cooling are better than those of R134a spray cooling under the same experimental conditions. Additionally, under low heat flux, R22 spray cooling is still expected to be completely replaced by R134a. Unfortunately, compared with the zero ozone depression potential (ODP) of R134a, R22 (ODP of 0.055) will deplete the ozone layer, leading to the greenhouse effect. Meanwhile, R134a is simple to react with water and in the closed-loop spray cooling systems, and the corrosive chemicals generated will damage the metal. Therefore, the abovementioned reasons limit the application of R22 and R134a in electronic spray cooling. Zhou et al. [53,72] conducted a comparative experimental study on the heat-transfer dynamics of transient spray cooling with different cryogenics (R134a, R407C, and R404A). On an epoxy resin block, R404A produces the best cooling capacity, namely the highest heat flux and lowest surface temperature, which means R404A could be a substitute for R134a. Subsequently, considering the need for environmental protection and energy-saving, Lin et al. of the same group [65], using a zero-ODP coolant and R410A (boiling point of -51°C at 1 atm) as the spray fluid, achieved the CHF of 264 W/cm^2 while maintaining a target surface temperature lower than 30°C .

Spray cooling data of different working fluids in the reviewed literature are summarized in Table 1. Overall, spray cooling with green and safe cryogens of low boiling point has strong application potential for removing high heat flux and maintaining low surface temperature. Taking advantage of the low boiling point, high latent heat, and high working pressure, using R410A as the working fluid in a closed-loop spray cooling system can obtain a strong cooling effect and reduce the size of the entire system, thereby improving the thermal management performance of electronic chips. However, up to now, there has been limited literature available on spray cooling with R410A as the working fluid. In-depth experimental studies are still required to be carried out to compare the cooling performance of spray cooling using different volatile cryogens.

Table 1. Spray cooling data of various working fluids in the reviewed literature.

Authors	Working Fluid	T_b (°C)	h_{fg} (kJ/kg)	T_{sat} (°C)	T_w (°C)	CHF (W/cm ²)	HTC (W/cm ² K)
Lin and Ponnappan [55]	Water	100	2256	70	121.1	>500	9.78
Mudawar and Valentine [61]	Water	100	2256	23	145	638	2.0615
Chen et al. [62]	Water	100	2256	25	137.8	945.7	8.38
Pais et al. [63]	Water	100	2256	24–29	>100	>1200	-
Lin and Ponnappan [55]	Methanol	64.7	1109	53	129	490	6.45
Zhou et al. [56]	Ethylene glycol (EG)	-	-	30	>110	143.79	1.75
Zhou et al. [56]	65 wt% EG-water solution	-	-	30	>100	144.50	2.6
Bhatt et al. [60]	500 ppm ethanol solution	-	-	25	-	200	0.9
Liu et al. [57]	4% n-propanol + 96% water	-	-	25	120	420	4.75
Lin and Ponnappan [55]	FC-87	-	-	54	97.7	90.0	2.06
Lin and Ponnappan [55]	FC-72	56	88	42.5	79.9	83.5	2.23
Visaria and Mudawar [69]	FC-77	97	89	25	129.4	349	-
Hou et al. [70]	R22	-40.8	233	-3	26.8	276.1	7.1
Hou et al. [13]	R134a	-26	217	-10	46	117.2	2.55
Tian et al. [72]	R134a	-26	217	-	-46.1	29.49	-
Tian et al. [72]	R407C	-43.6	250	-	-55.9	36.41	-
Tian et al. [72]	R404A	-46.8	207	-	-57.9	37.74	-
Lin et al. [65]	R410A	-51	279	-11.7	30	264	21

T_b , T_{sat} , and T_w are the boiling point at 1 atm, the saturation temperature of coolant corresponding to spray chamber pressure, and the average temperature on the hot surface, respectively. h_{fg} refers to the latent heat of vaporization at 1 atm.

2.2.2. Soluble Additives

Recently, researchers have been inclined to improve cooling performance by modifying coolant properties, which refers to the method of adding nanoparticles (NPs) [73–75], surfactants [76,77], dissolving salts [78], water-soluble polymers [79,80], and other additives to the pure working fluid to change its surface tension and other characteristics. The most widely applied surfactants are cetyltrimethylammonium bromide (CTAB) as cationic, sodium dodecyl sulfate (SDS) as anionic, and polyoxyethylene (20) sorbitan monolaurate (Tween 20) as non-ionic additives.

Qiao and Chandra [76] explored the heat-transfer enhancement by addition of the surfactant (SDS) to water spray. Through the visualization of spray cooling on the test surface, it was found that adding surfactant can accelerate the bubble nucleation and foaming of droplets, thus enhancing the boiling heat transfer. In air-atomized spray cooling, CHF may be attributed to the insufficient liquid supply caused by droplet entrainment, splashing, and expulsion from nucleate bubbles [81]. Thus, Jia and Qiu [82] found that

the addition of surfactant decreases the atomized droplet diameter and the liquid film thickness, which leads to larger stable CHF and lower superheat.

Cui et al. [83,84] conducted a series of experimental studies to demonstrate the effect of the addition of dissolving salt additives (Na_2CO_3 , NaHCO_3 , Na_2SO_4 , MgSO_4) and dissolving gas (CO_2) on the spray characteristics. When the surface temperature is too low to initiate nucleate boiling, dissolving gas promotes the evaporation of the liquid film, while the dissolving salt additive has the opposite effect. In the cases of nucleate boiling regimes, however, the dissolving salt additive has a positive effect on the formation of bubbles.

Bandaru et al. [85–87] examined the enhanced cooling effect of types and concentration of surfactants on air-atomized water spray, using SDS, CTAB, Tween 20, and mixed-surfactant additives (e.g., SDS-CTAB, SDS-Tween 20, and CTAB-Tween 20). The experimental results revealed that for a single surfactant, the cooling performance of Tween 20 is the best in three different types of surfactants. With the increase of surfactant concentration, the CHF experiences a process of increasing at first and then decreasing with a maximum value of 398 W/cm^2 , owing to the influence of bubble accumulation. Besides, the mixture of nonionic and ionic surfactants provided better heat-transfer ability compared with those of the individual surfactants. Liu et al. [88] performed similar experimental work and discovered that the addition of Tween 20 or CTAB in water was able to obtain a lower surface temperature and a higher heat-transfer coefficient (HTC) but increased the cooling non-uniformity (CNU). Besides, the inclined spray method benefits the HTC of spray at high surfactant concentrations.

Cheng [26,78] proved that both high-alcohol surfactant (HAS, i.e., 2-ethyl-hexanol or 1-Octanol) and DSA (NaCl or Na_2SO_4) can significantly enhance the heat transfer of water spray cooling, especially 2-ethyl-hexanol. However, the enhancement mechanism of HAS and DSA are different. The addition of HAS reduces the surface tension of the working fluid, which is conducive to forming smaller atomized droplets and enhancing the droplet-film impact. In comparison, DSA increases the surface tension and stabilizes the liquid film separating bubbles, thus promoting bubble boiling heat transfer. Furthermore, Zhang et al. [89] indicated that each of the four kinds of HAS has an optimal concentration to achieve maximum heat-transfer performance. In further study, the theoretical analysis of the same group later reported that the improvement in heat exchange by HAS mainly depends upon the increase of droplet diameter and decrease of surface tension.

2.2.3. Nanofluids Adopted in Spray Cooling

The physical properties of the working fluid can be changed by adding a small amount of nanoparticles (NPs), showing its potential in the improvement of the cooling performance for electronics [90]. Hsieh et al. [91,92] dispersed seven different types of nanofluids (Ag, Al, Al_2O_3 , Fe_3O_4 , SiO_2 , TiO_2 , and MWCNTs) in deionized water, and the average HTC as well as the associated CHF were improved significantly. Among the various nanofluids tested, Al_2O_3 with an average dimension of 5–30 nm and volume fraction of 0.1% showed the maximum CHF of 375 W/cm^2 . In this case, it only took less than 8 s to reduce the heater surface temperature from 400°C to 160°C .

Malý et al. [93] checked the effect of NPs concentration of Al_2O_3 , ZnO, CuO, and $\text{FeCl}\cdot 4\text{H}_2\text{O}$ on the spray cooling of a targeted surface using a pressure-swirl atomizer. It was found that the addition of nanoparticles with high thermal conductivity had no significant effects on the atomization mechanisms, but was beneficial to improving the dynamic viscosity of the resulting nanofluid, resulting in a slight decrease in the diameter of the atomized droplets and the spray-cone angle.

Chang et al. [94] investigated the comprehensive influence of spray-spurt duration and NP concentrations on the surface wettability and spray-cooling performance. In a given spurt duration, the surface wettability increased with the increase of NPs added. Moreover, for the nanofluids with NP concentrations of 0.001 and 0.05 vol%, respectively, the surface wettability and cooling performance both increased with increasing spray spurt duration.

In 2016, Tiara et al. [95] reported that addition of surfactants into nanoparticle suspensions is advantageous for improving the stability and uniformity distribution of nanofluids. Meanwhile, surfactant additives also help to change the surface properties and thermo-physical properties of nanofluids, such as viscosity and thermal conductivity [96,97].

Bandaru et al. [98,99] conducted a series of experiments on the effect of dispersant type on heat-transfer enhancement of air-atomized spray cooling. The dispersants used include SDS, CTAB, Tween 20, and polymer surfactant polyvinylpyrrolidone (PVP). In comparison with the nanofluid without the surfactant, water- Al_2O_3 nanofluid with the surfactant could enhance the cooling rate significantly via the improvement of thermal conductivity. Among the dispersing agents used, the addition of non-ionic surfactant exhibited the best augmentation of boiling heat transfer. Thereafter, the same group [100–102] synthesized a brand new nanofluid by using a co-precipitation technique, through with Cu–Zn–Al LDH nanofluid was utilized as a coolant to experimentally study the effect of molar ratios of Cu and Al, and dispersant type on the thermo-physical properties, stability, and heat-exchange performance of LDH nanofluid during pressure atomized spray. The maximum value of cooling rate and average heat flux for SDS-aided Cu–Zn–Al LDH nanofluid could reach $174.8\text{ }^\circ\text{C/s}$ and 170 W/cm^2 . In contrast with water-based cooling, its cooling rate and average heat flux increased by 30.7% and 14.2%, respectively.

Using Tween 20 as the dispersant, Wang et al. [103] analyzed the heat-transfer performance of three water-based nanofluids with different concentrations. The experimental results revealed that with increasing concentrations of the tested surfactant, the surface hydrophilicity and the corresponding CHF of nanofluids were improved due to the decrease of the solid/liquid contact angle. Jun et al. [104] employed CTAB as the dispersant for ZrO_2 and SiO_2 nanoparticles and SDBS as the dispersant for Al_2O_3 and TiO_2 nanoparticles. The effects of the concentration of the surfactant additives, as well as the type and concentration of nanoparticles on the cooling performance were tested. Optimized concentrations of nanoparticles were proven to exist for the best cooling effect. Owing to the Brownian motion, the presence of very small quantities of nanoparticles is conducive to disturbing the liquid film and improving the heat-removing capability. For the high-concentration nanofluid, the agglomeration of nanoparticles leads to increase of fluid viscosity and surface tension, yielding poor atomization and deterioration of heat-transfer performance. What's more, the best heat transfer appears when the mass fraction of CTAB is 0.005% and SiO_2 nanoparticles is 0.2%, which is attributed to the enhancement of lower concentration of CTAB on the dispersion of nanoparticles.

In addition to the abovementioned regular nanofluids, Akram et al. [105–112] conducted a series of numerical investigations with hybrid nanoparticles and inclined magnetic fields, after which they discussed the effects of the different parameters of nanoparticle diffusivity. The results revealed that as a class of novel nanofluids, hybrid nanofluids (e.g., Sisko nanofluids, Jeffreys nanofluid, Oldroyd-4 constants nanofluids, and Prandtl nanofluids) have better thermal effectiveness than regular nanofluids. These works are of great value and provides a model to study the flow and heat transfer of nanofluids in the presence of a magnetic field and double-diffusivity convection.

Over the last two decades, the effect of nanofluids on surface heat-transfer performance has still been controversial, which hinders the application of nanofluids in spray cooling [113]. Although the introduction of nanoparticles improves thermal conductivities

and heat-transfer coefficients of working fluids, the interaction between the nanofluid and hot surface, the properties (nanoparticles concentration, nanoparticle distribution, agglomeration, settlements, etc.), and wetting behavior of nanofluids are not thoroughly studied. Hence, the role of nanofluids in spray cooling should be further explored. In future theoretical research, determining the local nanoparticle distribution within an evaporating meniscus is essential for successful modeling [7].

2.3. Surface Modification

Surface modification is a universal strategy for each spray-cooling system regardless of the nozzle type and working coolant, usually in conjunction with other enhancement methods. Considering the significance of liquid film in spray-cooling mechanisms, this section categorizes cooling surfaces as macrostructures (mm) and microstructures (μm and nm), according to the thickness of liquid film in 10–1000 μm [6]. The complexity of spray cooling makes it difficult to explain the enhancement mechanism of surface modification. Principally, it can be summarized as the increase of heat-transfer area, improved wettability, flow optimization, and more active nucleation sites.

As for macro-scale modified surfaces, working fluid flows in a larger area with more intense turbulence. Normally, well-designed macro-scale surfaces perform better than ordinary fin surfaces with same heat-transfer area due to the facilitated liquid drainage and improved contact between the surface and coolant. Therefore, spray-cooling performance is improved in both single-phase and two-phase cooling modes, which means low- and high-heat flux stages. Researchers usually utilize their novel spray-cooling systems to study the influence of macro-structures. Yu et al. [114] developed a liquid nitrogen spray-cooling system with a low heat-transfer surface temperature. The straight-grooved surfaces with different groove depths were employed to obtain the optimal sample. Salman et al. [115] fabricated a surface with circular and radial grooves, which overcomes the shortcomings of fluid confinement by straight-pins. Zhou et al. [116] prepared a novel pyramid enhanced surface by the electrical discharge machining (EDM) method, which had a larger area and better flow pattern. Nevertheless, macro-modification does not always show effects. Wang et al. [117] indicated $0.5 \times 0.5 \times 0.2$ mm fins in 0.5 mm-distance structures will decrease spray-cooling performance, with superfluous wettability and a useless outspread area. Surface-modification strategies are crucial for the further development of high-efficiency spray cooling.

Micro-scale modification includes changing the roughness and specially designed nano-structure, which increases active nucleation sites and reduces the surface temperature at the onset of nucleate boiling. Therefore, micro-modification improves the high-flux stage in two-phase regimes with a relatively high surface temperature. The methods implemented include EDM, photoetching, coating with particles or nanowires, electroplating, and common machining involving sanding and blasting. Generally, these methods can combine with macro-structure modification, except in minority cases such as sanding. Composite structural surfaces utilize the advantages of both macro- and micro-modifications and yield better performance than single ones. Nevertheless, the lack of an appropriate thermal insulation material makes it difficult to obtain high CHF due to the insupportable surface temperature, which could melt the insulation material and cause leakage in the closed spray-cooling system. Hence, some researchers pay more attention to HTC instead of CHF. Surface-modification strategies for spray cooling from the recent literature are summarized in Table 2, which involve both macro- and micro-structures.

Table 2. Surface-modification strategies for spray cooling.

Scale	Author	Enhancement Strategy	Working Fluid	Highest Heat Flux (W/cm ²)	Related Surface Temperature (°C)	Enhancement Rate
Macro	Yu et al. [114]	Straight-grooved surfaces with different groove depths	Liquid Nitrogen	106.8	~127	64.2% in HTC
Macro	Wang et al. [117]	Cubic pin fins with different lengths on enhanced surfaces	Water	643.4	50.1	54.4% in Heat flux, 57.4% in HTC
Macro & micro	Liu et al. [118]	Straight and pin fins. Flat surfaces with different roughness by EDM (electrical discharge machining)	Water	~600	~120	136% in HTC for straight fin, 288% in HTC for pin fin
Macro	Salman et al. [115]	Circular grooves with radial grooves	Water	~286	~90	80% in HTC
Micro	Muthukrishnan and Srinivasan [119]	Micropillar arrays	Water	~830 (CHF)	~120	25% in HTC
Macro & micro	Zhou et al. [116]	Pyramid and square fined Surfaces with silica nano-porous	R410A	330 (CHF)	~10	60% in CHF (marco), 85% in CHF (marco&micr)
Micro	Chen et al. [120]	Nanowire arrayed surfaces	Water	243 (CHF)	~120	110% in CHF
Macro & micro	Wang et al. [121]	Electrochemical corrosion surfaces, porous surfaces, and hybrid surfaces with straight-fin surfaces coated by a porous layer	Ammonia	350	~−15	200% in heat flux
Macro & micro	Xu et al. [122]	Cubic pin fins with irregular ZnO nanowires	R134a	180 (CHF)	~73	59% in CHF, 42% in HTC
Macro	Liu et al. [123]	Straight fins	Water with different surfactants	~43	~55	16.36 °C lower on surface 33.04% in HTC
Macro	Silk et al. [124]	Cubic pin fins, pyramids, and straight fins	PF-5060	140 (CHF)	~70	46% in HTC

Table 2. Cont.

Scale	Author	Enhancement Strategy	Working Fluid	Highest Heat Flux (W/cm ²)	Related Surface Temperature (°C)	Enhancement Rate
Micro	Bostanci et al. [125]	Electroplated-microporous surface sanded surface blasted surface	R134a and R1234yf	370 (CHF)	36.1	38.8% in CHF for R134a, 34.2% in CHF for R1234yf
Micro	Kim et al. [126]	Micro-porous particle coated surfaces with different particle size	Water	~550 (CHF)	~110	130% in HTC
Micro	Silk and Bracken [127]	Surfaces bonded and S-Bond soldered with 5.9 mm-high porous POCO HTC foam	PF-5060	133	120	66% in CHF
Micro	Augusto et al. [128]	Surface brazed with 5 mm-high copper foam	R134a	30 (CHF)	/	139% in HTC
Marco and micro	Bostanci et al. [129]	Pyramidal fins, triangular straight fins, rectangular fins, and square pin fins; indentations and protrusions fabricated by particle blasting and thermal spray coating	Ammonia	910 (CHF)	~53	18% in CHF 161% in HTC
Micro	Thiagarajan et al. [130]	Surface coated with 100 µm-thick 57% porosity 3M L-20,227 powder	HFE-7100	~188	~80	80% in CHF

2.4. System and Environmental Parameters

Besides the factors mentioned above, system and environmental parameters can also have non-negligible effects on spray-cooling systems, such as non-condensable gas, gravity, etc. Puterbaugh et al. [131] and Elston et al. [132] controlled the amount of air dissolved in FC-72 by changing the total pressure of the spray system, and then studied the effect of the non-condensing gas on spray-cooling heat transfer. Their results showed that the presence of air changes the system pressure, but has a minimal effect on the cooling performance of the spray system. Lin and Ponnappan [55] experimentally investigated the cooling ability of water spray, methanol, and FC-87, and obtained the CHF of 500 W/cm², 490 W/cm², and 90 W/cm². More importantly, their results showed the effect of non-condensable gas on heat-transfer performance. Such gas yields finer droplets and thinner films formed on the cooling surface, and the air flow replaces the evaporating vapor on the surface to reduce its partial pressure, thereby strengthening the surface evaporation. As a result, the CHF is increased, but the spray-cooling curve shifts to a higher wall temperature. Horacek et al. [133] also studied the influence of non-condensable gas content in the coolant on the spray-cooling heat-transfer mechanisms and obtained similar conclusions. However, Liu et al. [134] used PF-5060 and FC-3284 as working fluids in a closed spray system to further study the effect of air. This study showed that the surface temperature will increase and spray-cooling efficiency will decrease with the increase of air volume fraction (from 0.06 to 0.65) at the same heat flux. In addition, the secondary nucleation induced by air may weaken the effect of total chamber pressure on the heat transfer of spray cooling. Liang and Mudawar [135] pointed out that the presence of non-condensable gas will make the design of the spray system more complicated after summarizing the previous research work. To our knowledge, the negatives owing to the non-condensable gas outweigh the positives. Even worse, the presence of non-condensable gas can damage the compressor or pump, which is detrimental to the long-term and stable operation of the system. In the design and work of spray systems, therefore, attention should be paid to removing impure gas [136].

Spray cooling is recognized as the most promising next-generation thermal management technology, and its application in the aerospace field is another research focus [137]. Therefore, it is of profound significance to explore the effect of gravity on spray systems. In the early stage, Golliher et al. [138] constructed a visual spray-cooling system and used the NASA elevator to change the gravity field. They successfully visualized spray flow on the cooling surface under different gravitational fields, as shown in Figure 2. Different from the normal gravity, the surface tension would dominate the heat transfer and flow regime change during the spray-cooling process in the micro-gravitational field. Ohta et al. [139] conducted a nuclear boiling experiment by parabolic flight under 0.01 times gravity. Their results revealed that microgravity makes it more difficult for bubbles to escape from the liquid film in the nucleate boiling stage, which leads to the deterioration of heat-transfer performance. Buoyancy is the main driving force for bubble separation under normal gravity, but it is difficult to produce buoyancy under microgravity [140]. Tatiana et al. [141] used visual image-processing technology to study the liquid film produced by the spray impact on heated targets. From their results, it was found that the average thickness of the liquid film on the cooling surface would increase in microgravity environment, which weakens the system cooling performance. By contrast, Elston et al. [142] tested the FC-72 spray system in different gravity fields and found that the heat-transfer performance under microgravity was the best, which is contrary to Tatiana's conclusion. Kato et al. [140] also used gravity-reducing aircraft to control the gravity between 0.01 g and 2 g, and studied the spray cooling characteristics of different working fluids in this range. Their results demonstrated that when taking CFC-113 as the working fluid, CHF decreases by about 10% at 0.01 g relative to 1 g of gravity. When taking water as the working fluid, however, CHF increases by about 15%. It can be seen that the research on the effect of gravity on the cooling performance of spray system is still inconclusive, and the conclusions obtained from different experiments are quite different, or even opposite. The authors believe that

the main reason is that the duration of the microgravity field generated by either the lift or the parabolic flight is only a few seconds during the experiment, which causes an inability to effectively study the heat-transfer and flow characteristics of the spray. In future work, the effect of gravity may be better understood and explained if the rate of bubble formation and detachment on the cooling surface is taken as the penetrating point of the study.

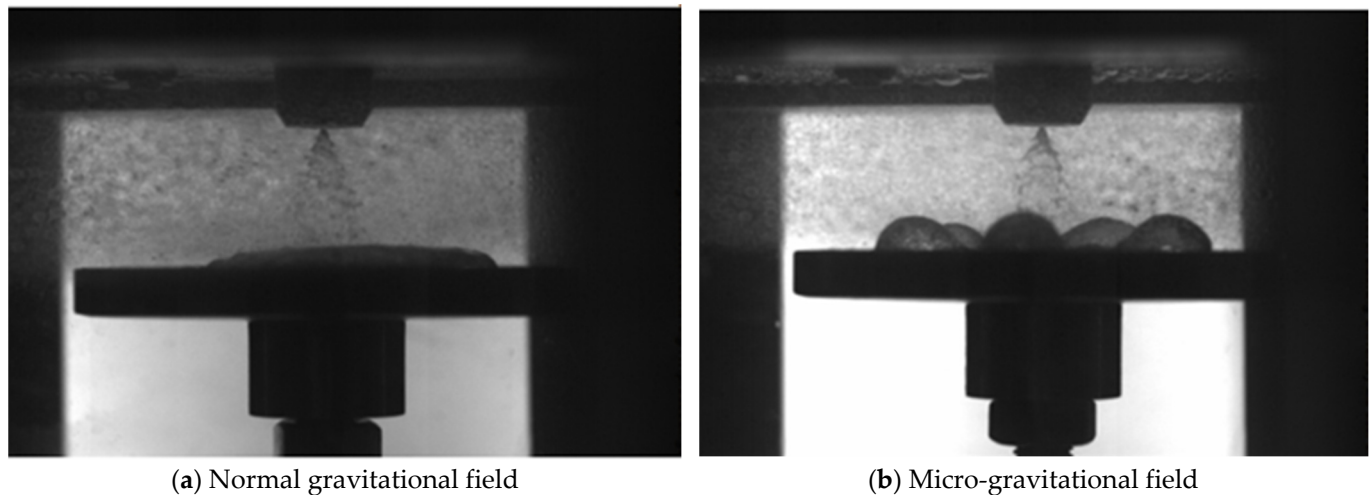


Figure 2. Spray pattern under different gravity fields [137].

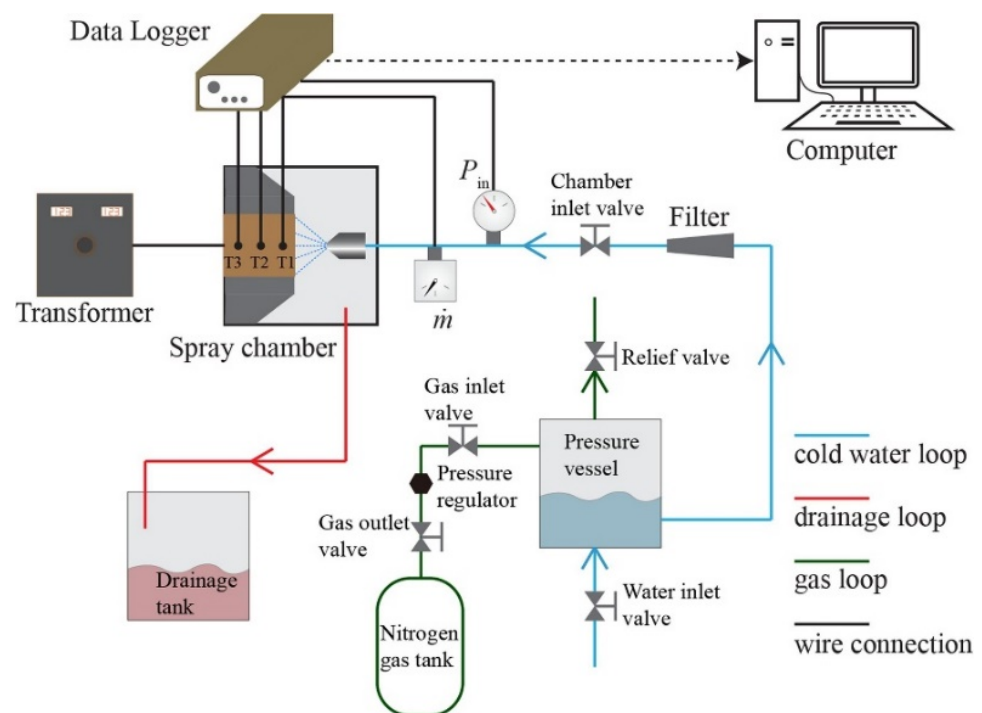
In addition to the non-condensable gas and gravity factors, other system and environmental parameters have also been studied. For example, Xie et al. [143] studied the effect of different spray cavity designs and configurations on the spray system. In their spray system, CHF could be increased by 65% by increasing the internal volume of the spray chamber.

3. Practical Applications and Challenges

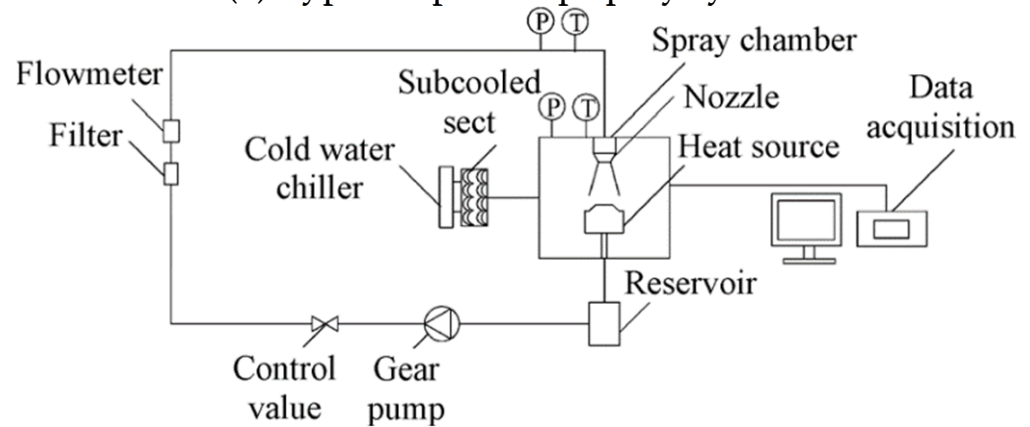
With great potential [144], spray cooling technology has gradually entered the practical stage. In order to adapt to the equipment with different structures in different fields and the changeable thermal control environment, researchers have explored and studied the diversified designs of spray-cooling systems.

3.1. Configurations of Spray System

Generally speaking, spray-cooling systems can be divided into open-loop systems and closed-loop systems, as shown in Figure 3 [118,145]. In the open-loop systems, pressure vessels or liquid pumps are usually used to provide circulating power. This system configuration can easily change the type of working fluid to meet different heat dissipation requirements and the needs of different working environments. Nevertheless, an additional vacuum pump is needed to maintain the low-pressure environment in the spray chamber, and it is difficult to adjust the cavity pressure. Furthermore, the open system increases the consumption of coolant. Compared with open-loop systems, the internal circulation of working fluid in the closed-loop systems avoids repeated charging, which reduces the amount of refrigerant used. However, the design and construction of the closed-loop systems are relatively complex due to the high air tightness requirement, which will hinder the large-scale promotion of the spray system in practical industrial applications.



(a) Typical open-loop spray system



(b) Typical closed-loop spray system

Figure 3. Schematic diagram of spray-cooling systems [118,145].

Spray systems can be equipped with one or more atomizing nozzles according to the requirements of the practical system. Xue et al. [146] studied the effect of the number of nozzles from 1 to 4 on the cooling performance under the same cooling surface area of 595 cm^2 in a liquid nitrogen spray system. Figure 4 shows the arrangement of their 2×2 multi-nozzle array. They found that an increased nozzle number and injection pressure will increase the overall cooling rate and decrease the surface temperature, but adversely affect the temperature uniformity. In a water spray-cooling system, Bandaru et al. [147] applied a 2×3 nozzle matrix to FeCrAl alloy foil with surface area of 96 cm^2 . Figure 5 shows the schematic diagram of their spray chamber design. At the heat flux of 250 W/cm^2 , this experimental system can control maximum surface temperatures below 83°C . At present, multi-nozzle arrays are mainly used for large area cooling of heat sources. If the size, number, or arrangement of the array nozzles could be flexibly adjusted and designed according to the shape and size of the cooling device, more efficient cooling performance could be achieved.



Figure 4. Configuration of multi-nozzle systems.

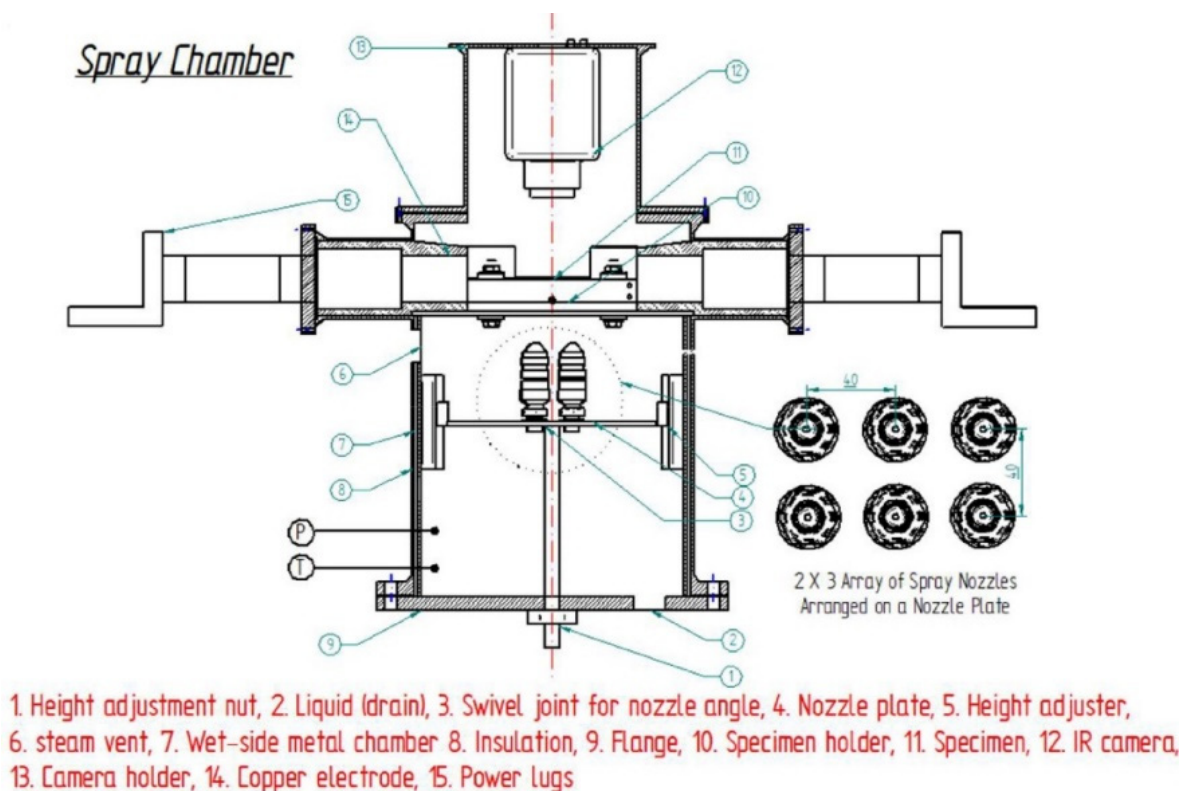


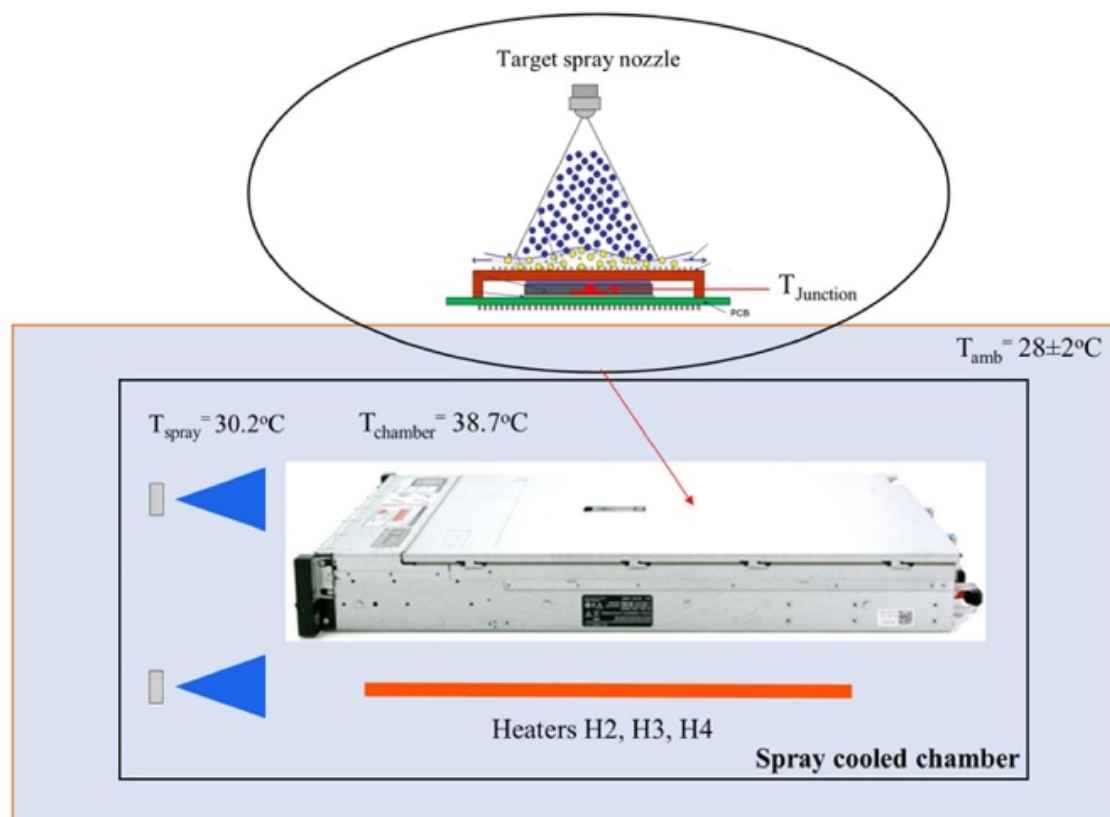
Figure 5. Schematic diagram of a spray chamber designed by Bandaru et al. [147].

3.2. Applications of Spray System

Spray-cooling technology has great application prospects in the heat dissipation of high-power electronic equipment, electric vehicles, and reactor pressure vessels. Researchers have designed various spray-cooling systems based on different shape and size requirements and heat dissipation needs of heat sources in different fields. Next, examples and reviews of recent industrial applications of spray cooling systems are given.

3.2.1. High-Performance Computer and Data Center

At present, the power density of high-performance computers and data centers has exceeded 100 W/cm^2 , and the value is still growing rapidly [148]. Spray cooling, as the most likely thermal management solution to replace traditional cooling, has attracted the attention of number of researchers. Cheng et al. [26] designed a compact spray-cooling system to cope with heat dissipation from a hot plate in narrow space. Their spray chamber, equipped with a multi-nozzle array, was just 26 mm thick. The experimental results showed that the system allowed the heat flux of 102.6 W/cm^2 to pass through heating module of size $30 \text{ mm} \times 30 \text{ mm}$ when the superheat was lower than 45°C . Kandasamy et al. [149] sealed a microprocessor in a spray cavity, connected multiple cavities in parallel in the loop of the cooling system, and proposed a new thermal management scheme for data centers, as shown in Figure 6. Compared with conventional air-cooling solutions, spray-cooling systems could reduce the microprocessor temperature by approximately 7°C , and the temperature of data center could be maintained below 35°C after 4 h of continuous operation or 40 h of intermittent operation. Besides, the total power consumption of the spray-cooled data center could be significantly reduced by 25.8% by removing the cooler system and CRAH unit, the energy-intensive component, from the air-cooled system.



(a) Spray-cooled chamber

Figure 6. Cont.

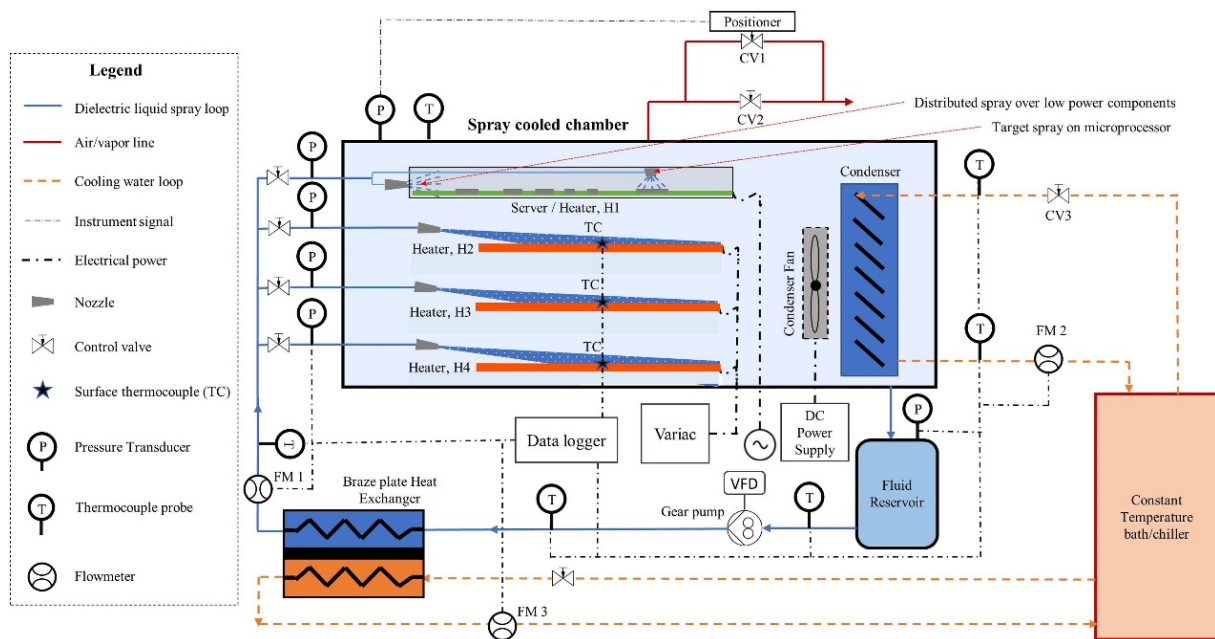


Figure 6. Spray-cooling system for a data center [149].

3.2.2. Aerospace and Spacecraft

To meet the cooling requirements of space thermal management under various operating conditions, Wang et al. [150] innovatively combined a mechanically pumped fluid loop (MPFL) and spray-cooling technology in an efficient way, as shown in Figure 7. Multiple experimental tests showed that the system could maintain a cooling surface temperature between 35.9 °C and 41.9 °C under thermal loads of 50 W to 150 W, and maximum heat flux could reach 468.8 W/cm² when the superheat was 70 °C in the spray-cooling module. They claimed that the system could largely ignore the effect of gravity, so it could be suitable for high-power onboard electronics, such as onboard laser diode.

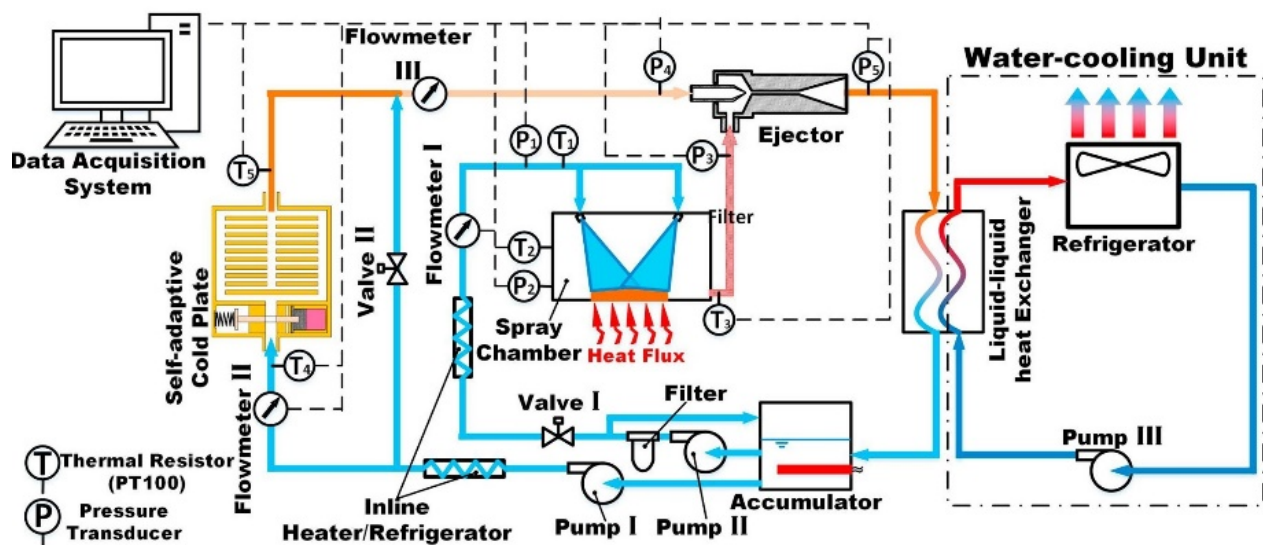
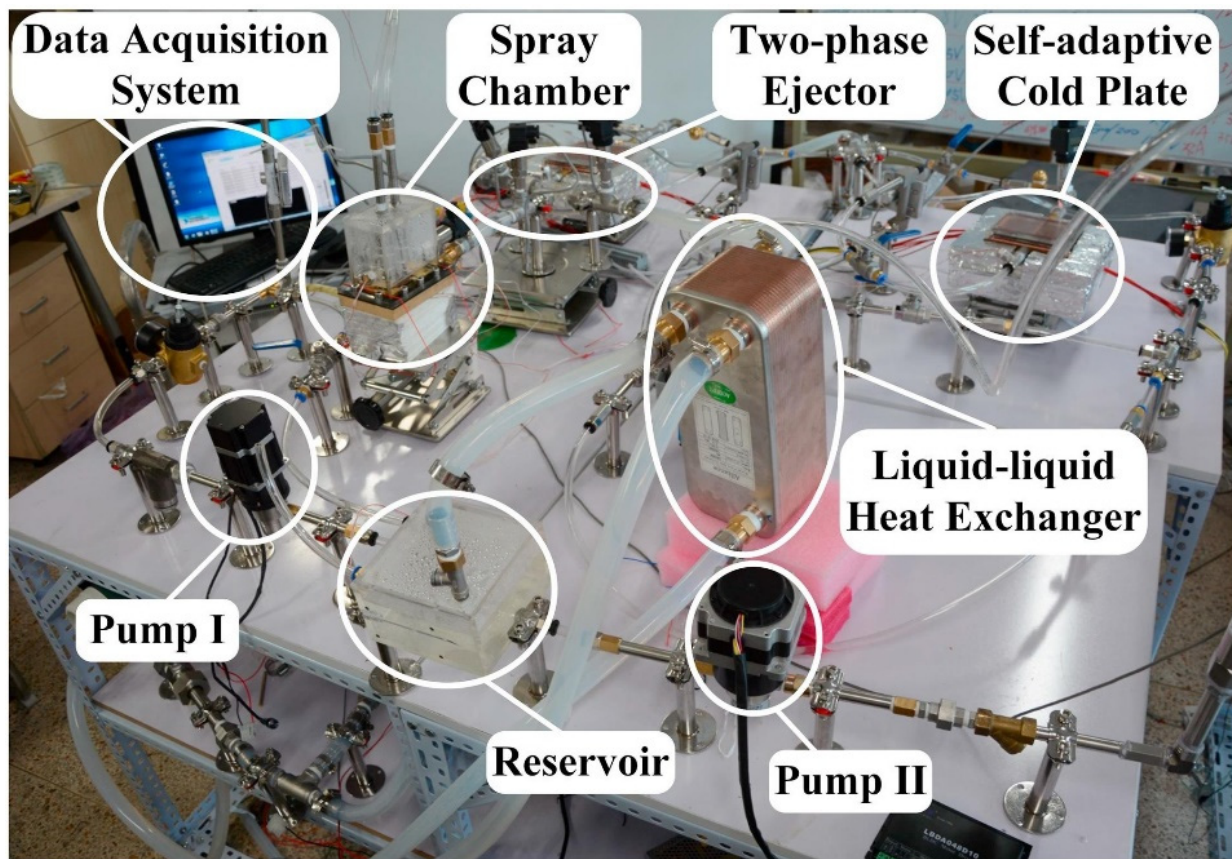


Figure 7. Cont.

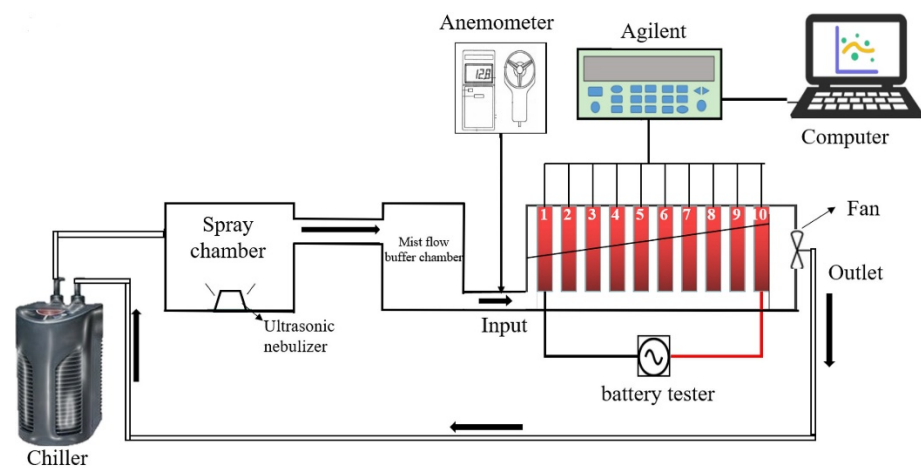


(b) Photo of the system

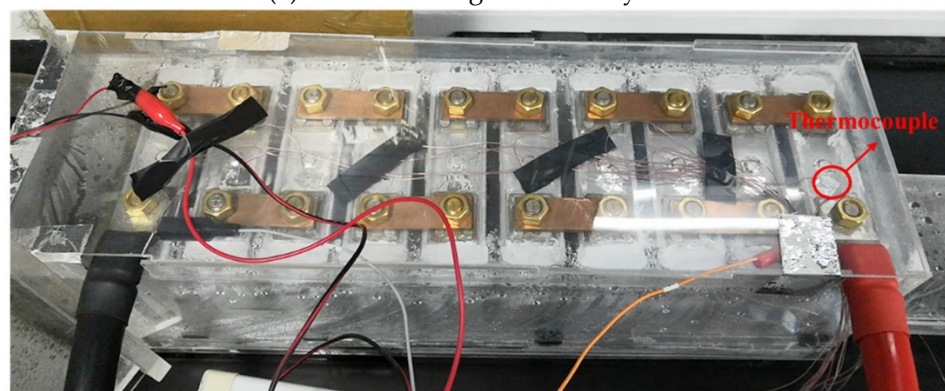
Figure 7. Spray system for space thermal management designed by Wang et al. [150].

3.2.3. Hybrid Electric Vehicle

Wu et al. [151] applied spray-cooling technology to the heat dissipation of battery components. They used commercial prismatic lithium battery to replace the conventional copper heating module in the spray chamber, as illustrated in Figure 8. By adjusting different spray concentrations, the heat-transfer coefficient reached $201.0 \text{ W}/(\text{m}^2 \cdot \text{K})$ under the optimal cooling mode, which is 409.3% higher than that under forced air cooling. In addition, spray cooling provided a lower temperature rise for the battery module, with maximum temperature rise no more than 10.3°C and more uniform temperature distribution. Dong et al. [152] put forward a new horizontal motor-cooling technology by mixing air and insulating spray as the working medium. They sealed the main part of the motor in a square chamber for using mixed air and spray cooling, as presented in Figure 9. The air flow is provided by fans and the spray is atomized by nozzles surrounding the motor. Below the cavity are the liquid supply pumps, and above is a water cooler to condense the high-temperature spray so as to ensure the cooling cycle of the system. Their experimental results showed that the spray-cooling system could control the stator coil temperature under 22°C and increase the average heat-transfer coefficient by 28% to 53% compared with air cooling. These studies will provide guidance for the application of spray-cooling technology in the field of hybrid electric vehicles.

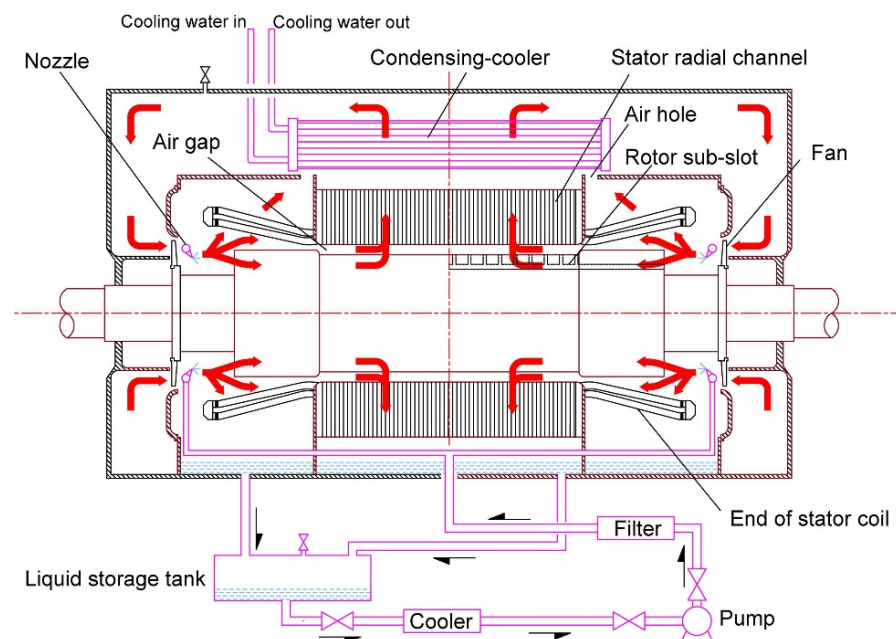


(a) Schematic diagram of the system



(b) Photo of the system chamber

Figure 8. Spray system for battery thermal management designed by Wu et al. [151].



(a) Schematic diagram of the experimental setup

Figure 9. Cont.

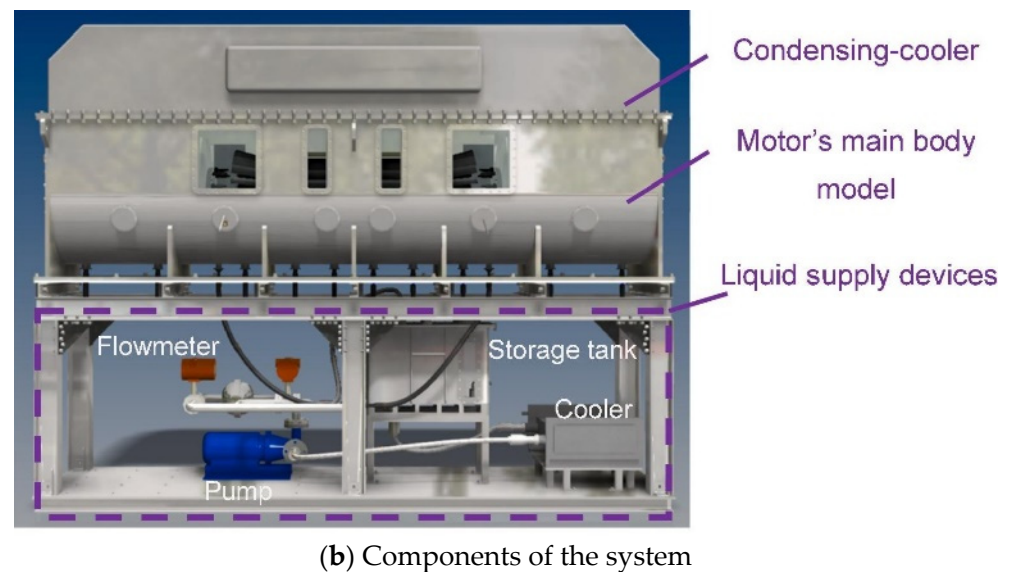
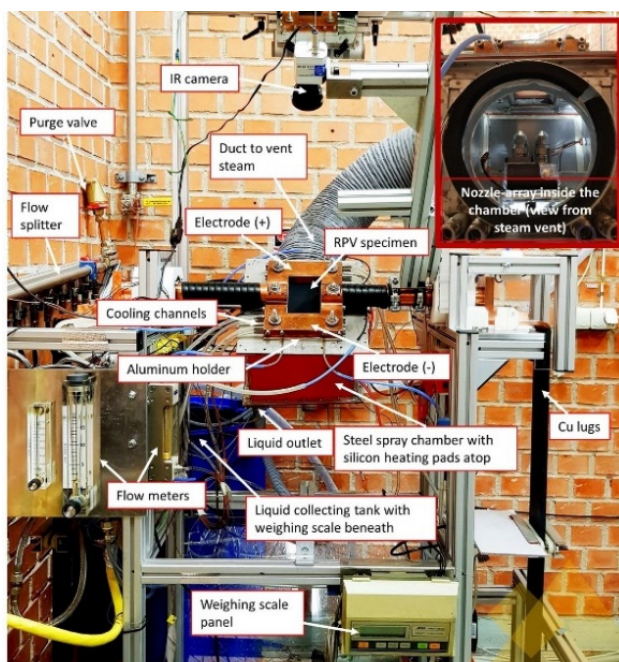


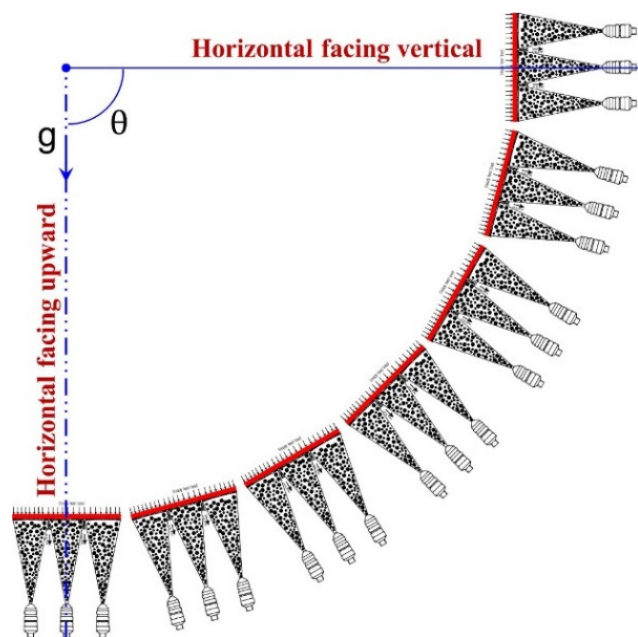
Figure 9. The new horizontal motor-cooling system [152].

3.2.4. Reactor Pressure Vessel

Bandaru et al. [153] studied the heat-transfer performance of the array spray impinging on the surface of the reactor pressure vessel. Figure 10a shows their spray experimental system. A steel heating plate of size $120 \text{ mm} \times 80 \text{ mm} \times 0.15 \text{ mm}$, combined with 2×3 matrix multi-nozzle spray system constitutes the test section. In the experiment, the entire external surface of the pressure vessel was simulated by continuously adjusting the surface inclination angle (0° – 90°), as shown in Figure 10b. The experimental results demonstrated that the multi-nozzle spray cooling system could safely remove high stable heat flux of 297 W/cm^2 from the surface of vessel steel, which is greater than the CHF generated by the traditional natural convection RPV pool cooling reactor vessel. This confirms that spray cooling has good prospects in the heat dissipation of reactor pressure vessels.



(a) Spray experimental system



(b) Experimental scheme

Figure 10. Spray system for a reactor pressure vessel designed by Bandaru et al. [153].

3.3. Challenges and Future Work

In view of the latest research progress on spray cooling technology, this section discusses and analyzes the scientific challenges and technical bottlenecks encountered by spray cooling technology in the theoretical research and industrial applications, thereby providing reasonable speculation on the research directions of great significance in the future.

- (1) Owing to the multiple parameters and their complicated interrelation in the spray cooling system with different equipment and experimental conditions, the heat-transfer laws derived are less universal, and in absence of the refinement of crucial factors to establishing a more unified heat-transfer theory. For example, for the same kind of coolant, the optimal parameters (flow rate, subcooled degree, etc.) to achieve the best cooling performance are usually different in different experimental systems.
- (2) There are still great challenges in the quantitative measurement of atomization characteristics of the neat nozzle outlet, especially lacking reliable technical means for the accurate measurement of droplet temperature and velocity in the low-temperature fog field without interference.
- (3) Some present strategies to enhance the cooling performance of spray systems are of low practicality in industry. For instance, microstructure/nanostructure surface modification are expensive, and macroscopic ribbed fin structures cannot achieve the desired improvement in cooling performance of spray systems due to the design requirements of electronic device package sizes. In future work, 3D printing or all-in-one packaging technology can be innovatively and reasonably introduced.
- (4) To adapt the dynamic heat load of electronic equipment, the cooling ability can only be regulated by adjusting the system pressure, yielding the delayed control of spray system, especially in the case of rapidly changed dynamic thermal load. In future, it is urgent to increase the response speed of the spray system to reach the steady state, i.e., the ability to quickly match the cooling capacity with dynamic heat load.
- (5) As a key part of spray-cooling systems, the structural design of nozzles is generally more complex. When system works for a long time, the nozzle is prone to blockage or corrosion. For some compact spray systems, the pipeline will also suffer blockage and throttling faults. In future practical system designs, nozzle structure, pipeline laying, maintenance difficulty, and other factors should be considered.
- (6) Current electronic devices tend to be more miniaturized and integrated. How to adapt complex spray-cooling systems to the limited space in small electronic devices is critical to further develop the application of spray-cooling technology.

4. Conclusions

This paper reviewed the latest progress in spray cooling technology, including the heat-transfer mechanism of spray cooling, the study of relevant factors affecting spray-cooling systems, the configuration and design of spray-cooling systems, and the practical industrial applications of spray-cooling technology. The following are the main conclusions of this work:

- (1) Compared with the traditional cooling technology, spray cooling has advantages of small heat-transfer temperature difference, large cooling capacity, and uniform temperature distribution on the cooling surface, which has great potential in the future heat dissipation of high-power equipment.
- (2) There are many parameters affecting the cooling performance of spray systems, including spray parameters, types of working fluid, surface modification, and environmental parameters. Complicated interrelation exists between these multiple parameters, and the parameter sets to achieve optimal cooling effect are generally different.
- (3) Spray cooling systems have been designed for high-performance computers and data centers, spacecraft, hybrid electric vehicles, and reactor pressure vessels, but have not been widely industrialized. Compared with traditional thermal management solutions, spray cooling shows better cooling performance and temperature-control characteristics.

- (4) The scientific challenges and technical bottlenecks encountered in theoretical research and industrial application of spray-cooling technology were discussed and analyzed, and the directions of important research significance in the future were reasonably speculated.

We hope that this work can provide guidance for more in-depth and clear theoretical research of spray-cooling technology and more extensive and practical industrial applications.

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Nomenclature

CHF	critical heat flux (W/cm^2)
h_{fg}	latent heat of vaporization at 1 atm (kJ/kg)
HTC	heat-transfer coefficient ($\text{W}/\text{cm}^2\text{K}$)
SMD	Sauter mean diameter (mm)
T_b	boiling point at 1 atm ($^{\circ}\text{C}$)
T_{sat}	saturation temperature of coolant corresponding to spray chamber pressure ($^{\circ}\text{C}$)
T_w	average temperature on the hot surface ($^{\circ}\text{C}$)
Δt	spurt duration (s)
Greek symbols	
η	cooling efficiency (%)

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