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A Review of Parameters and Mechanisms in Spray Cooling

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Abstract: Miniaturisation in avionics, electronics, and medical appliances has led to demands for rapid heat dissipation techniques. The spray cooling technique has gained importance recently due to its advantage over other cooling methods. Parameters affecting heat transfer mechanisms during spray cooling are contemplated. This review presents different heat transfer parameters and their effect on spray cooling by analysis from past studies. Heat transfer surface modifications and different coolant variations to enhance heat transfer effectiveness are also reviewed. Apart from high heat flux having more applications, low heat flux studies have also grabbed the researchers to find solutions with a temperature range lower than 250˚C. Therefore, the upcoming spray cooling technology will have broad applications that will contribute to the maximum efficiency of the heat removal rate.

Keywords: Miniaturisation; Heat transfer; spray cooling.

1. Introduction

Heat transfer is a significant unit operation essential for achieving desired products and maintaining device functionality [1]. The heat dissipation studies of high heat flux find interest due to rapid changes in electronic systems, satellite electronics, radars, air conditioners and refrigeration, avionics, microelectronics, rocket nozzles, high Mach aircraft engines and medical imaging systems [2-4]. Few industrial food applications, such as solid lipid particles, can be encapsulated by spray chilling to enhance the bioavailability of bioactive compounds [5]. Machine parts used in aerospace applications are cooled during machining by cryogenic and high-pressure cooling [6]. During quenching, metal alloy parts are cooled at high temperatures to obtain desired microstructure and mechanical properties [7].

Thermal management in miniature equipment necessities rapid heat dissipation by techniques such as coolant flow through spray cooling, microchannels, porous media and jet impingement cooling [8, 9]. Research on a two-phase spray of atomised droplets is gaining interest [10]. Spray cooling is used in refrigerators [11]. Low heat flux application of spray cooling using a spray chamber as the evaporator is incorporated into refrigeration systems [12]. Spray cooling heat transfer is affected by spray parameters (volumetric flow rate, nozzle-to-surface distance, droplet size, spray pattern), surface parameters (temperature, roughness), fluid parameters (properties, ambient pressure), and enhanced surfaces. [13-16]

Cryogenic spray cooling finds application in laser surgery to avert the danger of thermal injury by cooling selective locations, limiting laser radiant exposure, and improving therapeutic outcomes [17]. Applications of Spray oil cooling systems for electric vehicle driving motors are studied [18]. Cryogenic fluids (compressed carbon dioxide and liquid nitrogen) were employed to cool carbon fibre reinforced polymer plates by throttle, and evaporative cryogenic fluids and the plates exhibit structural intactness [19].

The vigorous heat dissipation in micro miniaturisation on board, a gas-atomised spray cooling system can be used [20]. Due to the proliferation of high-power electronics and airborne equipment, the rapid and efficient cooling of the systems is gaining prominence. Heat sinks also find applications in microfluidics devices, computer chips, hybrid vehicles, and micro-electromechanical systems [21, 22].

Different cooling techniques are available and used based on heat flux application. Each method has its advantages and disadvantages. Two types of cooling techniques are available based on liquid cooling technology: direct and indirect cooling. Direct cooling involves direct contact between the liquid coolant and the heating surface. In indirect cooling, the liquid coolant achieves cooling without contacting the heating surface. Spray cooling and Jet impingement fall under direct cooling, and heat exchangers and micro-channel are categorised under indirect cooling. In Jet impingement cooling technology, liquid sprays at high speed on the target surface. Very high heat transfer coefficients are formed under the film made by jet impingement. The boundary layer thickens on the surface due to fluid flow in the radial direction, minimising the heat transfer. This disadvantage limits the use of single jet impingement. Parameters such as jet geometry, swirl pattern, velocity and configuration should be optimised to enhance cooling using a jet impingement system. Micro-channels consist of minimum channel dimensions, which prove advantageous for achieving a high heat transfer coefficient.

Micro-channels can use Single-phase flow and two-phase flow of liquid. A single-phase microchannel is the most viable method. It enhances surface and flows boiling systems [23]. Spray cooling is the most advanced and efficient direct cooling technique for dissipation of low, high, and ultra-high heat flux [23]. Cheng et al. [24] have presented the progress of heat transfer in spray cooling technology. They have outlined the spray characteristics, influence factors, fluid characteristics, and external environmental characteristics. The heat transfer mechanism in different boiling regimes, such as single-phase and two-phase, is described to understand the heat transfer performance. In a single-phase regime, liquid film convection significantly influences heat transfer. In a two-phase regime, the nucleation of bubbles plays a vital role in spray cooling by removing latent heat. Factors influencing spray cooling are overviewed to study the optimisation of spray parameters and enhance heat transfer rate. They concluded that spray cooling technology is advantageous in high heat dissipation capacity. Hence, it is a widely used method for high heat flux removal. Flash evaporation cooling is emerging as the expansion of spray cooling technology with a remarkable cooling capacity [24]. This paper aims to review the progress in surface engineering-enhanced steady-state spray cooling. It provides a map of mechanisms that can aid in the design of engineered surfaces for spray cooling. The paper reviews progress in surface engineering at different scales, evaluates and compares performances, and discusses and summarizes enhancement mechanisms.

2. Evolution of Two-Phase Cooling Systems

Two-phase liquid heat dissipation schemes involve removing high heat fluxes by micro-channel heat sinks, jet impingement, and spray cooling. Jet-impingement cooling has a tremendous scope in cooling of temperature-sensitive devices [25]. A miniaturised microchannel heat sink enhances the heat removal in tubes of less than 1 mm [26]. Spray cooling offers the advantages of high cooling effectiveness and high flux heat dissipation. Single-phase cooling in small channels leads to high-pressure drops [27].

Two-phase micro-channel cooling occurs due to partial heat consumption of the liquid by evaporation. The latent heat exchange maintains temperature uniformity. The pressure drop issue in two-phase flow is caused due to friction in the channels [28, 29]. Additionally, the cooling performances can be enhanced by using extended (micro-structured) surfaces and special coolants [25]. A spray nozzle utilises the liquid momentum, atomises the fluid stream into fine droplets and bombards them onto the heated surface. The breakup increases the coolant's surface area to volume ratio and helps produce a uniform heat distribution and subsequent temperature drop due to incipient boiling [30]. The momentum of droplets ensures liquid penetration through the vapour barrier created by nucleating bubbles, replenishes the surface, and is beneficial to high flux cooling [31]. The disadvantage of spray cooling is the high-pressure drop during liquid atomisation, and increased probability of clogging [32].

Spray cooling and jet impingement are promising techniques for high heat flux cooling applications. Sleiti and Kapat [33] and Pereira et al. [34] remarked that heat transfer performance is similar to jet impingement and spray cooling; however, spray cooling offers the advantage of lower coolant requirement but consumes more pumping power.

3. Spray Cooling Mechanisms

Spray cooling heat dissipation depends on film thickness and velocity. The film thickness develops on the grooved surfaces, and the velocity depends on the type of fins (parallel and circular) and is independent of the surface temperature [35]. Spray cooling finds applications in high-concentration photovoltaic systems to reduce contact thermal resistance. Back surface spray cooling increases the performance of the system. [36, 37]. A spray cooling system application designed for a data centre in a tropical country based on the microprocessor temperature exhibits a better efficiency than an air-cooled scheme and eliminates the need for a chiller [14].

Understanding spray cooling mechanism needs knowledge of surface morphology, evolution and regimes of liquid film, wetted area, contact line length and velocity [21]. Extensive studies have been conducted on fractal-shaped structures causing boundary layer interruption and chaotic advection that promotes heat transfer without a modest change in pumping power. Spray cooling for high flux dissipation involves studies on nozzle arrangements, configurations for uniform flow distribution, temperature distribution and coolant drainage [38]. Experimental studies indicate surface roughness and macro-structure topology enhance spray cooling heat transfer and are found to increase by 116% and in the range of 136% to 288% straight fin and pin fin, respectively [38, 39]. An analysis of copper open and closed micro pin fins cooled with deionised water reveals tip clearance enhances overall thermal performance and is based on Reynolds number [21].

The vapour layer near the hot surface inhibits cooling at temperatures higher than the boiling point of the coolant. Fins destabilise the hydrodynamic vapour layer during film boiling and enhance heat transfer performance (maximum heat flux) by 230% compared to the plane surface [36]. The surface temperature distribution during spray cooling depends on droplet velocity, SMD distribution, fluid film thickness, and fluid film velocity in non-boiling and nucleate boiling regimes [40].

The heat transfer performance of spray cooling is studied for different orientations, and it is found that the dependency of the CHF reduces as the inlet pressure increases. [16]. CHF in spray cooling studies ascertains the effect of nozzle-to-surface distance. Maximum CHF is observed when the spray inscribes the heater surface [41]. Performance evaluation criteria for optimum surface geometry requires the consideration of shell side heat transfer area enhancement and fouling and should meet the standards for construction material, LMTD, and pumping costs [42].

This paper reviews the different spray parameters like pressure, velocity, nozzle to surface height and spray angle, and other fluid and surface type parameters affecting heat transfer efficiency. Surface modification improves spray cooling heat transfer by increasing turbulence, surface area, and wettability. Roughening, coating, and nanocoating can increase heat transfer area density. [43, 44] Pure water, water containing surfactants (SDS, CTAB, Tween 20), and ethanol-added water were used for high mass flux spray cooling tests. Heat transfer is inversely proportional to coolant surface tension and viscosity. In a two-phase nucleate boiling region, R410A had the highest heat transfer Gas-assist atomization produces small droplets with low velocity, and favours spray cooling [45-47]. In addition, the different enhancement techniques the authors apply give an overview of the parameters that help increase the heat transfer rate.

Chen et al. [48] studied the effect of droplet flux, droplet velocity, and Sauter mean diameter by individually varying them with a combination of operating pressures, spray nozzles and distance. The critical heat flux varies with droplet velocity and droplet flux but remains constant for Sauter's mean diameter [48]. Yang et al. [49] built a spray cooling model to study the cooling effect on extruded aluminium alloy plates with varying spray angle and distance parameters. The results have shown an increasing the spray angle improved the spray cooling efficiency [49]**.** The impact of the spray pattern was modelled using the data from spray cooling operations such as spray inclination angle, flow rates, and sub-cooling on a heated surface. It was observed that spray inclination angle had no significant effect. The maximum cooling performance was obtained from spray striking normal to the heated surface [50].

3.1 Spray Boiling and Quench Curves

The effect of heat transfer surface to spray cooling can be studied by boiling and quench curves [51]. The boiling curve provides inputs for cooling effectiveness and depicts the heat transfer regimes and the variation of heat flux with wall superheat, where wall superheat is defined as the difference between the wall temperature and liquid saturation temperature. The heat transfer regimes observed in the boiling curve are: single-phase liquid cooling, nucleate boiling, transition boiling and film boiling regimes. The nucleate boiling regime has the highest heat transfer coefficient. The onset of different regimes is indicated by boiling, critical heat flux, and minimum heat flux. The optimal cooling in low-temperature applications is achieved by maintaining conditions above the onset of boiling and below critical heat flux. In high-temperature applications such as quenching, the initial temperature lies in the film boiling regime. The minimum heat flux marks the transition from plodding film boiling to a much faster transition boiling. The boiling curve is a measure of surface effects, whereas the quench curve accounts for the thermal mass of the quenched part. The quench curve emphasises the Leidenfrost point, where significant changes in cooling rate can play a prominent role in quenched part's microstructure and mechanical properties. Quantifying spray cooling behaviour requires reliable predictive tools that cover all boiling regimes and transition points [12].

The spray cooling performance depends on the nucleate boiling regime, and the single-phase regime has considerably less influence. The spray nozzle-to-surface distance is adjusted to maximise CHF and single-phase heat transfer coefficient by Estes and Mudawar [51]. Zhu et al. [52] also infer a spray impact area affects CHF in single-phase heat transfer. Guo et al. [53] observed a thin high velocity film outside the spray impact area affects the spray heat transfer. Depending on the spray's volumetric flux, sprays can be described as dilute, intermediate, or dense. The droplet impact and spray volumetric fluxes are important parameters in spray cooling. Hence it is essential to study the impact of a liquid drop on a heated wall and the liquid film [54, 55].

The phase changes during spray cooling is attributed to convection, surface nucleation, and thin film evaporation [56]. The thin film on the surface helps heat conduction and is enhanced by the impact of the droplets. Secondary nucleation promotes the film's bubble nucleation and vigorous boiling [57]. The bubbles burst, producing smaller droplets, leading to secondary nucleation.

Shedd and Pautsch [58] state that phase change related experiments may not directly relate to conditions in space missions due to microgravity [59]. For spray cooling applications in aerospace, it is desired to design a spray cooling system that defies gravity [60].

4. Heat Transfer Enhancement

Pais et al. [61] examined the influence of surface roughness and attributed the cooling performance to film conduction and evaporation on smoother surfaces. Sehmbey et al. [62], and Ortiz and Gonzalez [63] infer that surface roughness enhances cooling performance for water pressure nozzles. Souza et al [64] report heat transfer coefficient enhancement in copper foam sprayed with refrigerant R-134a.

The heat transfer area can be enhanced by using fins or porous structures. The porous structure possesses a high exchange surface and causes a high-pressure drop on the porous matrix side [65]. Extended or passive heat exchangers impart high-efficiency cooling. The challenge is that the extended heat exchanger obtains maximum heat transfer with minimal pressure drop as pressure drops increase the power/pumping expenses [66]. Heat transfer enhancement due to fins depends on the material of construction of fins, particle deposition, surface treatment, and thermal contact [67].

The extended surfaces employed in cooling through radiation can be classified as randomly distributed particle structures, porous structures, multilayer structures, and metamaterials [68]. Finned surfaces increase heat transfer area density. A comparison of finned heat transfer surfaces with smooth surfaces exhibits a reduction of duration for quenching by 3.8 times and an increase of maximum heat flux (MHF) by 230% in the finned surface compared to the smooth surface [69].

Vorticity generated due to dimples increases heat transfer on the dimple and protrusion sides attributed to flow acceleration between protrusions [66]. Heat transfer in dimpled heat exchangers increases with the concentration of nano particles and mass flow rate [70]. Nanofluids enhance convection heat transfer in heat exchangers [42]. Phase change materials also possess a high heat capacity in their fusion temperature due to the latent heat [71].

Large heat transfer area density, low-pressure drop, and flow mixing in pin fins help heat dissipation in high heat flux electronic systems. The thermal performance of pin fins was modelled using a machine learning algorithm. [72]

The enhancement of heat transfer area density involves heat transfer through conduction-convection-radiation, possibly by incorporating extended surfaces in the form of fins [73]. Open-cell metal foams from aluminium alloys possess a surface area-to-volume ratio to the tune of 10,000 m^2/m^3 [42, 74, 75]. In pulsed spray cooling, the straight fin surface is more effective than the smooth surface and increases surface temperature non-uniformity [76].

4.1 Coolant Modification

The heat transfer capability of a thermal cooling system depends on the geometrical patterns employed and thermo-physical properties of the coolant. A nanofluid comprising of water - ethylene glycol is commonly added to maintain the cooling properties of water and leads to the compactness of thermal structures [77]. A numerical model for understanding the enhancement mechanism in spray cooling by high alcohol surfactant changes in weber number of droplets due to surface wettability variations in the spray characteristics and fluid properties such as surface tension, droplet diameter rate of liquid film formation and thickness of film [78]. Experimental investigations infer that spray cooling is enhanced by 55% a biosurfactant Rhamnolipid compared to conventional surfactant Tween 20 and is attributed to the nucleate boiling regime [79]. The dynamics of nonionic surfactant droplets on non-wettable surfaces depend on the molecular weight of the surfactants [80].

Infrared thermography revealed the thermal performance of spray cooling is enhanced due to the use of spherical alumina nanofluid [81]. Spray characteristics of methanol-in-diesel emulsions under evaporating conditions are studied using Mie-scattering and shadowgraphy techniques. [82]

The spray cooling performance can be enhanced by additives that alter the coolant contact angle, surface tension, and thermal conductivity. Qiao et al. [83] studied the effect of surfactant addition to coolant on nucleate boiling. Cui et al. [84] state cooling performance enhancement by foaming water spray due to salt addition (NaCl, $MgSO_4$ and Na_2SO_4, and $MgSO_4$) to water.

Spray cooling engineered surfaces in ultrahigh-power applications with ethylene glycol provides uniform, efficient cooling solutions and depends on the viscosity, heat capacity, mass flow rate, nozzle inlet temperature and thermal conductivity [55, 85]. In spray cooling, critical heat flux (CHF) is enhanced by reducing viscosity and surface tension and adding surfactant Tween 20 literature [45]. The heat transfer coefficient in spray cooling depends on the coolant temperature [86].

A novel "sub-zero" cooling supercritical CO_2 (Sc-CO_2) method uses CO_2 at Tc and Pc > 31.1 ^oC and 73.8 bar, respectively and is considered a green cooling technology [87]. The challenges of the biomedical implant industry (bone screws and knee joints) are cooling during the machining of nickel and titanium alloys, respectively. The electrostatic charging of cryo CO_2 spray produced chilling, resulting in refined grains and tool life enhancement [88]. Supercritical CO_2 cooling in conjunction with water-oil lubrication reduces surface defects during the milling of SiP/Al composites [89, 90]. Compressed carbon dioxide as a coolant plays a crucial role in the machinability of AISI-52100. The high-pressure throttling of CO_2 produces fog. The low-pressure dry ice blast leads to cooling by sublimation of dry ice, improves visibility of the cutting zone, precise penetration, machinability and cooling [91].A hybrid approach involving cryogenic cooling (CO_2 + MQL) for machining of Nimonic-80A. The experimental results indicate that the hybrid condition considerably decreases specific cutting energy requirements and the temperature by 34–53% compared with the MQL. XRD exhibits a smaller grain size and no phase transition [92].

4.2 Other Methods

Spray cooling performance can also be enhanced by jet actuators and intermittent or pulsed sprays. [17, 93-95]. Electrospray cooling [96], also improves cooling efficiency by generation of a fine spray through repulsion of droplets from each other.

5. Heat Flux and Heat Transfer Mechanism

Heat flux is the energy that flows per unit of area per unit of time. Based on operating temperatures, heat flux is classified into three types: High Heat flux (500-1500℃), Medium Heat flux (200- 600 ℃), and Low Heat flux (30-250 ℃). Constant heat flux (CHF) is the boundary condition that indicates the desired heat transfer rate. Low-temperature operations work below the CHF limit. Many studies have developed correlations for CHF to examine regimes of spray cooling. Though the heat transfer mechanism is wholly unknown, boiling regimes that form during heat transfer make phase changes. Phase change takes place in single-phase and two-phase. Wang et al. [97] studied the effect of severe heating on Reynolds number (Re), weber no (We), Jacob number (Ja), and dimensionless temperature on spray cooling beyond CHF. A closed-loop system prototype was built to study heat flux variations from 60 to 160 W/cm^2 with charging pressure. The heat transfer coefficient is studied till the CHF state is achieved. On heating, Re increased rapidly, and We increased with large fluctuations till CHF, after CHF both quickly decreased. Ja increased slowly before CHF and quickly grew after CHF.

In contrast, ε decreased gradually before CHF and decreased rapidly after CHF. The heat transfer coefficient in boiling heat transfer condition first increased, then dropped, and after CHF rapidly reduced. The heat transfer characteristics after CHF were recovered, reducing heat flux [49]**.** Bhatt et al. [98] performed spray cooling experiments using different coolant additions to water, such as acetone, benzene, and n-hexane, with low specific heat. High mass flux spray is used to overcome the problem of the formation of the film boiling phenomenon. The steel plate was used as the target surface to study the effect of various spray parameters. The heat transfer removal rate enhancement is optimised by varying flow rate, fluids, mass flux, and nozzle to surface height. High heat flux is achieved, and the heat transfer rate was observed to be improved by adding additives. CHF up to ~1.8 MW/m^2 is achieved for optimum 300 ppm concentration in the acetone-water mixture. Acetone-water mixture enhanced heat removal rate by increasing the contact angle with the surface.

Bhatt et al. concluded that metallurgical industries require fast cooling operations [98]. The increased use of diode lasers and electronic components results in higher heat density. The greatest challenge in thermal management is safely dissipating these large heat fluxes [99]. So, to overcome these problems, there is a need for cooling schemes that fulfil the requirements of desired thermal control. At first, microelectronic devices are used, which work efficiently at a surface temperature below 85 ℃ for general applications and below 125 ℃ for defence applications [27] . These devices' lifetime, performance, and reliability depend on their surface temperature. Air cooling systems have been introduced to thermal management systems. The air-cooling system is the simplest, affordable, requires a large surface area, and has a limited cooling capacity. For example, the maximum heat transfer coefficient of the standard fan is 150 W/m^2K. Because of this, the air-cooling system is suitable for low heat flux applications [23]. Engineers have proposed liquid cooling techniques for high heat flux to resolve these problems.

CHF in full-cone spray is dependent on geometrical parameters, nozzle flow parameters, spray hydrodynamic parameters, and thermophysical properties of the working fluid. Estes and Mudawar [51], Hou et al. [100], Moreno et al. [101], Chow et al. [102], Pais et al. [61], Toda and Uchida [103] suggest an increase in CHF with the enhancement of flow rate. Chen et al. [104] state that volumetric flow rate has a minor influence on CHF. Toda [105] states a positive relationship between an increase in CHF of water and droplet diameter. Estes and Mudawar [51] and Pais et al. [61] state CHF benefits from a decrease in droplet diameter. Chen et al. [104] state droplet size does not affect CHF.

6. Spray Cooling Technology for Low Heat Flux

Spray cooling is a mechanism associated with the impingement of spray of tiny droplets on a heated surface to achieve cooling. The spray cooling heat transfer mechanism is unique to other cooling methods by considering forced convection, surface evaporation of the liquid film and formation of nucleation sites [106]. Spray cooling is advantageous due to the higher heat transfer rate and uniformity in the heat transfer area [107]. Low heat flux spray cooling research below 250°C has potential for improved cooling performance, reduced energy consumption, and enhanced cooling of sensitive and complex geometries. Potential applications include electronics cooling, medical applications, food processing, manufacturing, and power generation. [108] Swirl spray cooling system studies on transient heat transfer efficiency at less than 300°C reveal four stages in the spray cooling process: Leidenfrost effect, liquid film formation, boiling, and convective evaporation [109, 110]. In these recent years, research has focused on enhancing heat transfer rate, including variations of various parameters. Table 1 shows a list of recent advancements from the past ten years. Yet, the heat transfer mechanism remains wholly unknown and needs a narrowed study on the influence of spray characteristics.

Table 1. *Recent investigations on spray cooling*

Fluid	q (Heat flux range)	Surface T, type	Pressure	Enhancement technique	Reference
Distilled water	100-250 W/cm^2	413 K	5 bar	Study of water as coolant along with addition of nano partciles, and surfactants to understand pool boiling and enhance heat transfer.	[81, 111, 112]

Deionised water and solution with surfactant	25x10^5 W/m^2	350 K, stainless steel	0-6×10^5 Pa	Heat transfer characteristics of non-boiling spray cooling are studied by surfactant addition	[40]
Alumina/water nanofluids	-	473 K, Teflon	100-300 Pa	Evaluation of HTC using alumina/water nanofluids	[113, 114]
Ammonia	450W/cm^2	323 K Copper	0.1-0.6 MPa	Using coolant ammonia heat transfer enhancement on micro-cavity surfaces was demonstrated	[115, 116]
Anhydrous ammonia	500 W/cm^2	411 K	550–570 kPa	Indentations, protrusions, and macro-scale fins enhanced the test surface with different geometrical shapes to investigate HTC	[117, 118]
R134-a	120 W/cm^2	319 K, copper	0.3 MPa	Influence of flow rate on closed loop spray cooling system	[100, 119]
Water	4895.525 kW/m^2	1123 K steel	4 bar	Evaluation of spray parameters from high heat flux plate	[120, 121]
Ethanol-water and ethanol-Tween20-water solution	2.1 MW/m^2	1173 K Steel plate	0.05–0.2 MPa	Heat transfer mechanism and spray behaviour at different flow rates was studied	[76, 107, 122]
Water, Water and ethanol	170 W/cm^2	400 K Copper	0.2-0.5 MPa	Heat transfer performance study to find the optimal volume fraction of ethanol in a mixture of water	[123, 124]
Water	70 W/cm^2	388 K	0.7 MPa	Microstructured surfaces were tested with different spray angles to determine heat transfer enhancement	[125-127]
Water and dextrose	1.39 MW/m^2	873 K, AISI 304 steel	0.2 MPa	Reducing residence time, enhanced and unaltered surface morphology is tried to obtain maximum heat removal rate	[128]

7. Spray Parameters

Spray parameters are the parameters that affect the spray cooling mechanism directly. Spray parameters include pressure and velocity of the fluid, nozzle to surface height and spray angle. Spray parameters significantly influence critical heat flux and heat transfer coefficient. Therefore, every parameter affects the spray cooling mechanism in its way. The impact of each parameter is observed to be dependent on the mass flux and varies based on the spray parameters variations during each experiment.

7.1 Hydrodynamic Parameters

Predicting the cooling performance of sprays involves parameters such as thermo-physical properties of surrounding gas, and surface parameters, thermo-physical properties of liquid, liquid type, liquid saturation temperature, geometrical parameters of spray nozzle, flow parameters, the thermal conductivity of the surface and ambient pressure [63, 129]. The most crucial parameters in spray cooling are droplet size, volumetric flux and velocity [48]. Surface roughness is also a crucial parameter that influences bubble size and departure pattern, droplet impact, heat transfer effectiveness, liquid film thickness, and vapour/gas entrapment [61].

Liquid droplet formation takes place at the tip of the nozzle. The atomised trajectory of droplets of different diameters travels at different velocities. The spray is characterised by mean droplet diameter. The droplets' diameter shall represent the spray's characteristics [130]. The concept of mean diameter was introduced by Evans [131]. Commonly used mean diameters are Sauter mean diameter (SMD) and mass median diameter.

SMD distribution is measured by simultaneous measurements of Mie scattering, planar laser-induced fluorescence and laser diffraction technique [132]. The three-dimensional characterisation of a spray in terms of its droplet SMD using the laser-induced fluorescence / Mie ratio technique [133]. SMD gains importance during subcooling. The nucleate boiling data can be fit using a correlation based on density ratio, Weber number and Jacob number [134].

One of the crucial hydrodynamic factors affecting heat flux and cooling performance of spray cooling is spray volumetric flux [131]. Literature refers to local spray volumetric flux and mean volumetric flux. Mean droplet velocity represents the velocity of spray droplets. Bolle and Moureau [135] proposed technique for the determination of mean droplet velocity and droplet size distribution.

7.2 Pressure and Velocity

Pressure and velocity are dependent on each other. For example, many papers show an increase in velocity with an increase in the pressure of inlet water. The other parameters that influence pressure and velocity include droplet flux, droplet size, droplet velocity, and Sauter mean diameter [16, 136].

Mzad and Khelif [85] conducted Heat transfer studies for spray cooling by simulation with the help of software COMSOL Multiphysics 3.5 to build a spray cooling model. The copper-beryllium sheet made by the computational model was used as a test surface to study the effect of varying pressures on it. The nozzle to surface height was kept fixed at 400 mm, and the pressure was varied from 1 to 4 bar. A correlation previously developed to predict heat flux rate and convection coefficient was applied to the simulation process. A derived equation traced the heat transfer coefficient. The heat transfer coefficients increased with an increase in water pressure in the range of 1 to 4 bar. HTC is also influenced by other parameters such as nozzle distance, water temperature, and impingement density. It was concluded that the method employed had an acceptable balance between computational efficiency and prediction [85]. Nayak et al. [85] investigated spray characteristics like inlet pressure, mass flux and flow rate for their influence on spray cooling. The inlet water pressure was raised from 2 to 4 bar. Steel surface plates with different thicknesses between 4 to 10 mm were used. The experiment was conducted at three heights of 120, 180, and 240 mm. Mass impingement densities at inlet air pressure 0-4 bar and water pressure at 3 bar were measured using a patternation. It was seen that the spay density increased with an increase in water pressure. In contrast, the spray density decreased with increased air pressure and constant water flow rate. With the increase in plate thickness from 4 to 10 mm, heat flux increased gradually. Also, it was seen that impingement density increased with an increase in the nozzle to surface height, and heat flux decreased from a height of 120 to 240 mm.

Finally, the observations infer that water flow rate alone cannot significantly enhance heat flux. [85]. Zhou et al. [85] investigated spray cooling performance at varying inlet pressures, spray height, heat flux, gravity angle, and nozzle atomisation effect. At the same operation conditions, it was observed that spray mass flow rate was mainly influenced by heat transfer of spray cooling. They used inlet pressures in the range of 4.5 to 7.5 bar increments of 1 bar. Three types of nozzles were used. Each nozzle had optimal spray height. At constant heating power, HTC increased, and surface temperature decreased with an increase in inlet pressure. This is because the rise in inlet pressure enhanced the atomisation effect of the nozzle. The spray flow rate and droplet velocity increased with an increase in inlet pressure. Dimensionless correlations were developed and analysed for water spray cooling. The results thus obtained helped improve prediction performance and develop new correlations. It was also concluded that evaporation intensity greatly influences spray cooling performance [85]. Electrospray cooling finds application in cooling remote surfaces and provides a good electro hydro dynamically induced convective air flow spraying range from 30^o to 90^o [137]. The temperature uniformity, Nusselt number and spray power consumption were analysed for direct spray oil cooling systems with different types of nozzles and different cooling oils [138]. The effectiveness of spray cooling for a radiator using water was modelled using the Euler–Lagrangian approach and validated experimentally as a function of spray angle and flow rates [139].

Spray pressure, droplet velocity, Reynolds number, and Weber number effect spray cooling. increasing spray pressure improves droplet speed and flow rate and decreases volume surface mean diameter, improving cooling in a spray and falling-film cooling system study. Higher spray pressure creates a turbulent, atomized spray with smaller, quicker droplets, higher Reynolds numbers, and much higher Weber numbers. Spray cooling droplet size and velocity impact heat transfer efficiency, therefore these relationships matter.

Table 2. *Effect of Spray Pressure on Droplet Size, flow regime, and heat transfer [140]*

Sl No	Spray pressure (bar)	Sauter mean diameter (microns)	Droplets velocity (m/s)	Reynolds number	Weber number
1	1.0	113	8.52	1081.8	113.7
2	2.0	94.5	12	1274.2	188.6
3	3.0	85.0	14.7	1403.9	254.6
4	4.0	78.9	16.98	1505.3	315.3
5	5.0	74.5	18.96	1587.1	371.2

Spray cooling in an argon environment of samples heated under a vacuum is studied. The conditions for experimentation imitate quenching operation and inhibit surface oxidisation. The results of spray cooling were compared and validated by Leidenfrost droplet model. Analysis of the quenching model indicates the existence of partial droplet–surface contact in the film boiling regime [141].

7.3 Nozzle to Surface Height

Zhou et al. [17] have proposed cryogen spray cooling with a novel hydrobarric pressure technique. The test surface material was made up of epoxy resin. The pressure varied between 1 to 100 kPa. At the same time, spray height was changed with values of 5, 10, 20, 30, and 50 mm. The experiment was carried out first at different heights at constant pressures. The optimum height was chosen, and at that height, pressures were varied. It was observed that surface temperature decreased with a decrease in pressure and height. Heat flux was enhanced by reducing the pressure to 10 and 1 kPa, achieving the highest height of 5 mm. The highest heat flux at 5 mm and 1 kPa pressure was obtained, whereas higher heat flux was obtained for the height of 20 mm and pressure of 50 kPa. Thus, it was concluded that the pressure heat flux could be increased at a short distance, and the temperature region broadened to achieve a maximum heat transfer rate [17]. The heat transfer mechanism on non-uniform surfaces is a sensitive factor in thermal management. Zhao et al. [16] have presented a study that explains surface temperature distribution on the non-uniform surface under different experimental conditions. The test surface was made of copper block provided with insulation at the side and bottom to avoid heat losses. An axial flow pressure swirl nozzle was used to carry out experiments. The nozzle to surface height varied from 18 to 42 mm with increments of 6 mm. The effect of varying heights on Sauter's diameter and the volumetric flow rate was determined. It was observed that droplet diameter distribution had no significant impact on the different nozzle to surface heights. The primary inference distribution of surface temperature non-uniformity concluded that a smaller Sauter diameter lowers the surface temperature and improves heat transfer. The model developed for heat transfer in spray cooling predicts non-uniformity in surface heat transfer at higher heat flux [16].

7.4 Spray Angle

Yang et al. [49] studied the effect of spray angle on an alloy of aluminium plates using a spray cooling model. The spray angles varied from 10˚ to 110˚ at 150 mm spray height and 0.3 MPa spraying pressure. The surface plate was heated up to 793 K. It was concluded that uniformity in cooling and higher efficiency could be achieved at an optimal range of spray angles from 70˚ to 90˚. At this range, cooling efficiency was obtained the highest [49]. Zhou et al. [142] presented a numerical study using a flat fan nozzle to determine spray angles. Ten flat fan nozzles were studied for their geometrical parameters and used for experimentation. Flow simulations of nozzles were generated from a computer program and read on CFD code. A model was built to predict and measure spray angles based on a standard spray pattern and observed that predicted and estimated spray angles were acceptable range.

Furthermore, they found a direct proportionality between nozzle input section diameter and liquid sheet thickness. Therefore, it was concluded that nozzles with the required parameters and conditions could be designed [143]. Halder et al. [143] employed a numerical and experimental approach to study the spray cone angle and coefficient of discharge of a solid cone swirl nozzle. Standard k–€ model of turbulence was used for theoretical predictions of swirling flow nozzle. The numerical predictions were verified by measuring the discharge and spray cone angle coefficient at different flow rates. Photographs of spray were taken to measure spray angle. It was seen that by increasing the swirl number, the spray cone angle increased. At the same time, the coefficient of discharge decreased to a point where the swirl increased and then increased with a decrease in the swirl number. On comparison and investigation, it was observed that predicted, and measured nozzle parameters have reasonable accuracy. Finally, a fair agreement was established for theoretical and experimental results [143].

7.5 Nozzle Type and Orientations

The atomiser and pressure nozzle are the two basic configurations of spray cooling nozzles [144]. Atomisers utilise a gas stream to form tiny droplets. Pressure spray nozzles rely on the momentum of the liquid to achieve droplet breakup or atomisation. There are five types of spray nozzles: the spiral type, the conical type, the square type, the sector type, and the target impact type. The spiral type nozzle may be the best for an indirect evaporative cooler application because it has a high coverage ratio, good uniformity, and a good water volume in the distribution area [145]. Pressure spray nozzles are classified based on the distribution of droplets across the surface as a full, hollow, and flat cones. The Figure 1 depicts the three droplet patterns from pressure nozzles. The full cone spray nozzles distribute liquid droplets across the entire impact circle and are preferred for spray cooling applications. A minimum nozzle-to-surface distance is required for pressure spray nozzles to produce a fully developed spray. The spray nozzles are usually mounted in a downward direction, but in special cases, other configurations such as upward-facing, horizontal, and inclined configurations are used. Space constraint issues can be addressed by tilting the spray from normal orientation relative to the surface or using micro-sprays that require much shorter breakup distances [50]. The cooling performance concerning orientation has been a topic of interest. Research by Liang and Mudawar [146] on nozzle droplet velocity emanating from downward and upward-oriented nozzles infers gravitational force that does not affect spray cooling performance. Other researchers make similar observations [120, 134]. Few researchers state that spray orientation influences cooling performance [147-149].

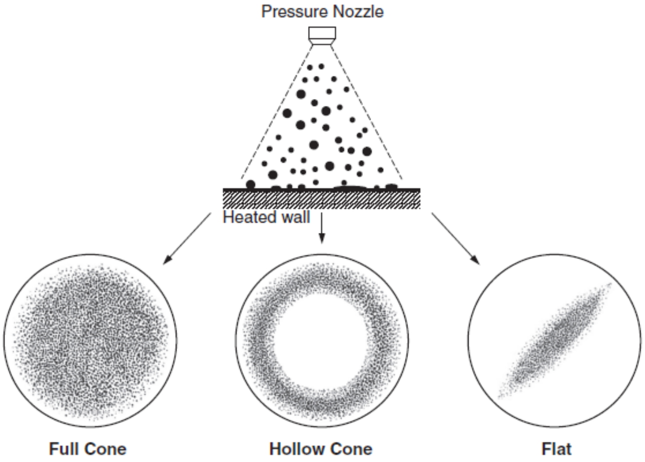

Figure 1. *Droplet impact patterns of pressure nozzles [146]*

Often large heat dissipating surface areas mandate the use of multiple spray nozzles. One of the engineering problems in spray cooling is corrosion, erosion of the interior portion of the nozzle and clogging of the nozzle. Estes and Mudawar [41] have recommended using filtration and stainless steel spray nozzles to overcome the issues mentioned above.

Different coolants and multiple nozzles are tested. The influence of parameters, namely film thickness due to pressure swirl nozzle, the distance between nozzle and surface, nozzle arrangement, heat sink size, coolant flow rate, heat capacity, and depositions, are studied. The effect on temperature uniformity, spray resistance, heat transfer coefficient, Nusselt number and spray power consumption is evaluated [18].

The efficiency of liquid utilisation at critical heat flux (CHF) depends on droplet Sauter-mean diameter, droplet velocity, and droplet flux [48]. Heat transfer during spray cooling depends on the type of extended surfaces and spray inclination angle [150].

7.6 Other parameters

Other than spray parameters, some parameters directly affect spray cooling. These include fluid type, surface type, additives such as surfactant etc. Fluid types can be varied or used in combinations to enhance heat transfer performance. Similarly, different surfaces can be used to find the optimum characteristics that affect spray cooling performance.

7.6.1 Fluid type

Different fluids or fluid mixtures are used to achieve maximum heat transfer efficiency. Many studies have observed that other solvents can be used in specific concentrations to increase the heat transfer rate, even with water. In a case study by Hou et al. [100], spray cooling studies were carried out using coolant R134-a using a full cone nozzle. The test surface was a copper cylinder (diameter 16mm) at a height of 13mm from the nozzle end. At different flow rates, the cooling performance of coolant R134-a was investigated. It was observed that convection dominated heat transfer. Thus, the effect of nucleate boiling was weak, which in turn had a slight influence on heat flux at different flow rates. The flow rate and heat flux relationships were proportional [143]. Freon-113 was chosen as a coolant by Ghodbane and Holman [143] because of its similar characteristics for direct immersion cooling of microelectronic components instead of dielectric liquids. Full cone circular and square hydraulic spray nozzles were used for spray cooling heat transfer. The liquid flow rate was changed to study the effects of spray droplet velocity, mass flux and droplet diameter on heat flux. As velocity is varied, the droplet velocity and diameter have an incredible impact on the efficiency of spray cooling. At varying heights, it was seen that spray cooling is effective at the shorter nozzle to surface distance [143]. Bhatt et al. [98] conducted spray cooling studies using a coolant mixture and compared it with water. The coolants ethanol-water, pure water, and tween20 ethanol-water combinations were used at different proportions. Spray cooling with ammonia sprayed by atomising nozzle ensures efficient cooling and high heat flux removal on extended surfaces with fins, protrusions and indentations. [117]

On increasing ethanol concentration in ethanol-water spray cooling, the heat removal rate was found to be improved. Ethanol-water-tween 20 mixture (2.1 MW/m^2) spray enhanced critical heat flux 1.6 times that of pure water (1.3 MW/m^2). Fast cooling with a rate of 141˚C/s was obtained [98]. Purified water and the mixture of ethanol and water with varying concentrations were investigated by Lui et al. [123]. The cooling performance was compared using a solid cone spray nozzle. It was observed that spray cooling performance was enhanced by adding ethanol to water. The research found that adding a volume fraction of 4% ethanol is optimal for improved heat transfer performance [147].

Investigations on spray cooling with LN_2 infer heat flux and heat transfer coefficient are inversely proportional to the size of the heated surface [151]. Spray cooling with LN_2 with multiple spray nozzles enhances cooling efficiency and increases with the number of nozzles, higher gas pressure and reduced gas mass flow rate [55]. Conventional thermal fluids may not dissipate heat in modern high-heat-flux devices. Hybrid nanofluids may increase spray cooling heat transfer. Due to more nucleation sites, water-based TiO_2 nanofluids boosted boiling heat transfer without changing spray characteristics [151, 152].

Novel heat transfer fluids, nanofluids, contain nanoparticles (metals, oxides, and carbides) in a base fluid (typically water). Nano fluids transmit heat better than base fluids, hence applications in cooling. Concentration enhancement increases cooling in most Nano fluids. Hybrid nanofluids and cylindrical nanoparticles are found to be useful in cooling PV systems. Pulsating Nano fluid cooling with multiple jet impingements is ideal for PV systems. Pulsing amplitude, Strouhal number, nanoparticle solid volume fraction, and impinging jet slot number effect Nano fluid cooling. Pulsating nano-jet cooling systems with alumina–water nanofluid and cylindrical nanoparticles work well for PV systems [153, 154]. Spray cooling is the appropriate and most efficient cooling system in space rocket propulsion applications [55]. Cryogenic LN_2 was used for spray cooling of titanium alloys.

7.6.2 Surface type

Hsieh and Yao conducted comparative studies on the effect of spray cooling heat transfer on a plane and micro-structured silicon surfaces [147]. This study reported that micro-structured silicon surfaces had effective heat transfer performance. Different heat transfer regimes were observed on the enhanced surface from which thin film showed efficiency for higher heat transfer rates [147]. Salman and Khan [136] studied heat transfer enhancement's effect on circular grooves in non-boiling regimes. Nozzle height was varied from 8-12mm, and the volumetric flow rate was varied from 115-177 mL/min. The heat flux decreased with an increase in nozzle height.

In contrast, heat flux increased with increased volumetric flow rate for the plain and enhanced surface [136]. The effect of R134-a sprays cooling was studied on a plain surface, copper foam surface, and copper grooved surface. A commercial full cone pressure-swirl nozzle was used for spraying. The copper foam's enhanced surface boiling curve was observed to have much larger heat transfer rates. The critical heat flux had no significant effect on the type of surface geometry used [155]. Salman et al. [156] studied three different surfaces' spray cooling heat transfer characteristics. The enhanced surfaces included surfaces with a combination of circular and radial grooves. Nozzle to surface height and the volumetric flow rate were varied. As spray height increased, the spray coverage area increased, increasing heat flux. It was concluded that the surface with radial and circular grooves has a higher heat removal capacity than only with straight grooves [156]. Investigations of spray cooling with liquid nitrogen (LN_2) on plain and grooved surfaces reveal that heat flux increases initially with groove depth, spray angle, and spray pressure, followed by a decrease. However, an increase in groove width leads to a decrease in flux. [90]. Applications of Spray oil cooling systems for electric vehicle driving motors are studied. Different coolants and multiple nozzles are tested. The influence of parameters, namely film thickness due to pressure swirl nozzle, the distance between nozzle and surface, nozzle arrangement, heat sink size, coolant flow rate, and heat capacity, depositions are studied. The effect on temperature uniformity, spray resistance, heat transfer coefficient, Nusselt number and spray power consumption is evaluated. [39, 138, 151, 157]

The details about spray cooling obtained from literature are described in Table 3. The spray cooling data infers several factors can influence the efficiency of cooling systems. These factors encompass the type of surface being cooled, the properties of the working fluid, the type of spray being used, the surface area available for cooling, and the mass flux of the fluid. In general, micro and hierarchical surfaces have superior cooling efficiency compared to smooth surfaces. Ammonia typically exhibits greater critical heat flux (CHF) values in comparison to R134a or water. The heat transmission performance may be influenced by the specific type of spray employed. The augmentation of surface area typically results in an elevation in cooling efficiency. An increase in mass flux can lead to an enhancement in cooling efficiency.

Nevertheless, the studies exhibit a considerable range of cooling efficiency, with values ranging from 16.24% to 84.76%. This vast variation underscores the susceptibility of cooling efficiency to a combination of conditions and experimental setups.

Table 3. *Spray cooling details from literature*

Spray Atomisation type	Surface type	Mass flux (kg/m²s)	Surface area (cm²)	Heat Transfer Coefficient (HTC) (W/cm²K)	Critical Heat Flux (CHF) (W/cm²)	Cooling efficiency η	Literature referred
Gas	Hierarchical	10.05	2.00	80.65	500.0	39.70 %	[110, 117]
Gas	Hierarchical	13.20	2.00	20.19	1090.0	60.20 %	[25, 110]
Gas	Hierarchical	10.05	2.00	19.78	910.0	66.90 %	[110, 117]
Gas	Smooth	10.05	2.00	29.41	500.0	38.82 %	[110, 117]
Gas	Smooth	10.05	2.00	18.14	780.0	57.65 %	[110, 158]
Pressure	Hierarchical	37.91	1.77	18.64	330.0	44.77 %	[15, 110]
Pressure	Micro	6.31	1.23	5.60	375.0	21.93 %	[110, 159]
Pressure	Micro	54.81	1.00	5.95	370.0	27.96 %	[110, 160]
Pressure	Micro	4.10	1.23	7.16	322.0	29.46 %	[110, 159]
Pressure	Micro	3.21	1.23	6.79	258.0	30.30 %	[110, 159]
Pressure	Micro	1.70	4.91	3.22	29.0	84.76 %	[110, 155]
Pressure	Nano	37.91	1.77	56.92	222.0	32.33 %	[15, 110]
Pressure	Smooth	4.10	1.23	6.73	175.0	16.24 %	[110, 159]
Pressure	Smooth	6.31	1.23	6.31	309.0	18.31 %	[110, 159]
Pressure	Smooth	3.21	1.23	5.96	155.0	18.37 %	[110, 159]
Pressure	Smooth	42.63	1.00	4.53	240.0	24.23 %	[110, 160]
Pressure	Smooth	37.91	1.77	5.33	200.0	24.81 %	[15, 110]
Pressure	Smooth	1.70	4.91	1.27	28.0	77.11 % .	[110, 155]

8. Spray Characterisation

A Phase Doppler Anemometry (PDA) was used to study the spray characteristics. During spray cooling heat transfer in a non-boiling regime depends on the working fluid's spray characteristics and thermophysical properties. The axial velocity and SMD of droplets were successfully correlated and dependent on dimensionless spray height, orifice diameter, spray cross-section radius, and Weber and Reynolds number of flow before liquid breakup [161].

Smooth surfaces delay boiling and reduce heat transfer. HFE-7100 boiling curve is linear for smooth surfaces, indicating single-phase heat transfer. Water boils on smooth surfaces. Boiling curves converge in two-phase cooling. Water heat transfer is less affected by surface roughness than pool boiling. Spray cooling is dominated by forced convective flow, which reduces the effect of surface roughness on wettability and nucleation sites (Figure 2) [108].

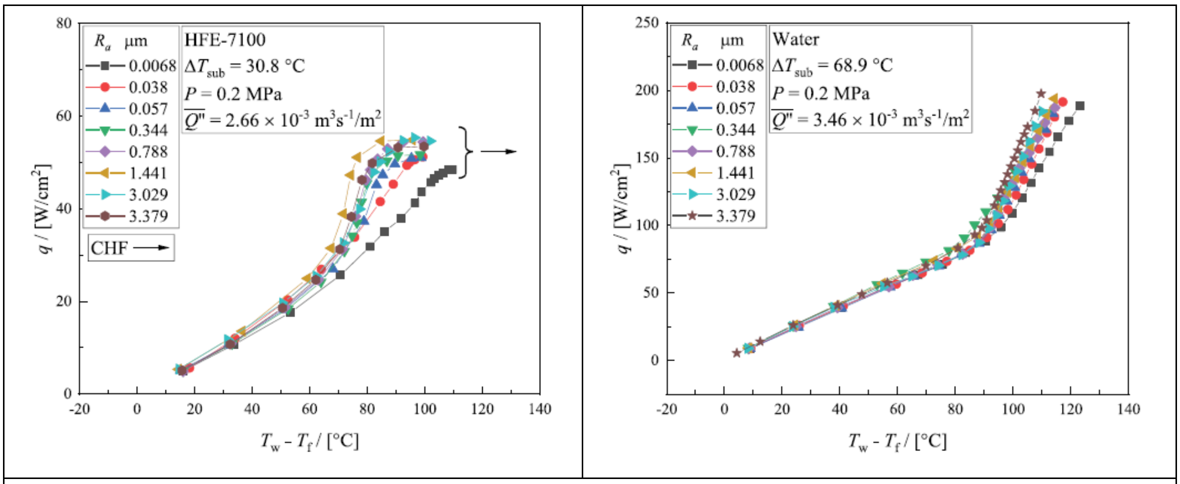

Figure 2. *Boiling curves of: (a) HFE-7100 and (b) water, for different surface roughness [108]*

9. Semi-Empirical Correlations for Spray Cooling

Empirical correlations were developed for critical heat flux in the transition boiling regime for spray cooling of a SS plate. [162] A generalised correlation is established to determine heat flux as a function of Weber number, Jacob number, wall superheat degree and mass flow rate [8]. An experimental study of heat transfer from hot surfaces below 400° C to water sprays was conducted for different boiling regimes of the quench curve. The correlations developed help develop quench curves for spray cooling employed in metal processing [130]. Correlations were developed for the different spray cooling regimes and transition points for heat diffusion models to predict the temperature-time relationship within the quenched part metal alloy parts [146].

CFD was used to characterise SMD, and weighted average velocity of droplets in multi-nozzle spray cooling, a mathematical model for the two-phase flow was developed. Simulations were carried out with Eulerian-Lagrangian approach [163]. Correlations for SMD of fluids with surface tension are developed to predict CHF data [51]. During spray cooling variations, average Nusselt numbers are related to film thickness along the spray cooling boiling curve [164].

Investigations on liquid nitrogen spray cooling revealed an effect of the heat sink's mass flux, spray height, and surface size. Correlations for Nusselt number at different stages of spray coverage were established [151].

Heat exchanger performance is dependent on the Colburn factor and Fanning friction factor. Perforations and dimples on the louvre surface increase the j and f factors [165]. The f and j asymptotes are related to the Reynolds number by a power law [42]. Investigations of heat flux in spray cooling indicate a strong correlation between Weber number, Reynolds number, Prandtl number, and Nusselts number [166].

The correlations developed by Mudawar and Valentine for the different spray cooling regimes and transition points. These correlations can be used to develop quench curves for spray cooling employed in metal processing [130]. The correlations developed by Estes and Mudawar for SMD of fluids with surface tension. These correlations can be used to predict CHF data [51]

The correlation developed by Agostini for heat flux as a function of Weber number, Jacob number, wall superheat degree, and mass flow rate. This correlation is generalized and can be used for a wide range of conditions [8]. The CFD model developed by Hou et al. for characterizing SMD and weighted average velocity of droplets in multi-nozzle spray cooling. This model can be used to study the effects of different spray parameters on droplet behaviour [163]. The correlations developed by Martínez-Galván et al. for relating average Nusselt numbers to film thickness along the spray cooling boiling curve. These correlations can be used to study the effects of film thickness on heat transfer [164]. The correlations developed by Liang and Mudawar for the different spray cooling regimes and transition points for heat diffusion models. These correlations can be used to predict the temperature-time relationship within the quenched part metal alloy parts [146]. These models are all well-established and have been shown to be accurate in predicting heat transfer in spray cooling.

10. Simulation Studies

The utilisation of spray cooling has been found to improve the efficiency of heat transfer. The determination of optimal values for spraying time, flow rate, air flow rate, distance, and heat source attributes is crucial in achieving the best heat transfer efficiency [167]. Individual parameters affect spray cooling. Numerical, computational and software tools are employed to study the effect of multiple parameters on spray cooling and simulate the spray cooling mechanism. Spray cooling simulations involve enhancement of heat dissipation during different heat transfer regimes, microscopic characteristics of the film, mist loading fraction, the distance between nozzle and heat transfer surface, and the effect of nozzle height and spray pressure on surface Reynolds number [168].

The spray cooling mechanism is modelled based on the Eulerian dispersed phase model and the Euler-lagrangian approach. [169, 170] Numerical models for LN_2 spray cooling were developed using Homogeneous Relaxation and Algebraic Interfacial Area Density models [60]. A CFD two-phase solver was employed to analyse and predict the increase in heat transfer due to sublimation and the user-defined function developed for the same [171].

Experimentation on laminar shape nanoparticles in a fluid mixture is modelled for thermal transport using Navier-Stokes equations and FEM [172]. The k-omega (k-) turbulence model of ANSYS - FLUENT has been used to simulate and validate spray cooling of water with carbon nanotubes [173]. Simulation studies are carried out for large eddies with the volume of the surface. The internal flow behaviour in the flow swirl injector is studied using computational fluid dynamics (CFD) software - FLUENT [60]. The internal flow behaviour in the flow swirl injector is studied using computational fluid dynamics (CFD) software - FLUENT. [174, 175]. The simulated and experimental data demonstrate a fair agreement. Spray cooling heat transfer is enhanced with a decrease in nozzle height and spray pressure increase. The results show that the heat transfer coefficient increases monotonously with the heat flux. The wall film is thinner in the nucleate boiling region with a smaller velocity than in the single-phase region.

Spray cooling involves both mass and heat transport. The mathematical model indicates convective heat transfer is improved by evaporative mass and heat transfer. A critical Reynolds number and critical film thickness indicate thermal inertia that suppresses the heat transfer process. [176]

Interphase heat transfer during spray cooling in compressed air energy storage (CAES) reduces gas temperature rise and improves efficiency. A computer model using Crowe number, a non-dimensional number linked to the effective polytropic index, was developed and compared with experiments [177].

The air-assist flat sprays computational process includes four steps: liquid simulation, atomization criterion, drop size and velocity specification, and scattered droplet trajectory computations. This simple, efficient, and resilient approach simulates drop size, velocity, impact pressure, particle-wall heat transfer coefficients, and spray contours [178].

11. Conclusions

Spray cooling heat transfer is a challenging but essential technology for miniaturized devices. The heat transfer performance of spray cooling is affected by a variety of parameters, including water inlet pressure, temperature, spray angle, volumetric flow rate, surface geometry, micro-level surface features, and fluid types. Increasing the contact angle, surfactants and other additives can reduce fluid surface film development. To explore these factors, spray cooling must advance. Focus on film thickness, critical heat flux point, and nozzle characteristics to improve heat transfer. Spray cooling regimes are crucial to many high-heat-flux removal applications.

In miniature electronics, spray cooling seems promising for quick heat dissipation. Water inlet pressure, temperature, spray angle, volumetric flow rate, surface geometry, micro-level surface properties, and fluid types affect spray cooling heat transfer microstructured. Modifying the heat transfer surface or utilizing different coolants improves spray cooling. Surface geometry or micro-characteristics can be altered. Coolant changes include adding surfactants or other fluids, alone or with water. Spray cooling works well in many applications, notably at high heat fluxes and low coolant flow rates. Improved wick ability, triple contact line length, active nucleation sites, and flow confinement for nanostructured surfaces and increased surface area, flow confinement, and triple contact line length for macrostructured surfaces are the main spray cooling enhancement processes.

Further research is needed in surface engineering, focusing on hierarchical structures that can combine improvement mechanisms at different length scales while taking into account scalability, durability, and quick and smart responses to changing environmental conditions. Spray cooling systems must be simplified and downsized to integrate spray cooling modules with high-power devices.

This comprehensive review of diverse aspects of spray cooling mechanisms and applications has resulted in a deeper understanding of the underlying heat transfer phenomena, identification of critical parameters influencing performance, and exploration of promising avenues for further advancement.

- Spray nozzles that provide uniform temperature, rapid heat dissipation, good corrosion resistance and self-cleaning from clogging are preferred.
- Volumetric flux, mean droplet diameter, and velocity are dominant spray and surface parameters influencing heat transfer effectiveness and performance.
- A vast literature database is available for comprehending heat transfer mechanisms in different regimes, coolants, surface characteristics, and nozzle types. There is a scope to

study bringing uniformity in surface temperature, predicting heat transfer coefficient for large surfaces. There is a need to develop generalised models and simulate the same. A gap exists in heat transfer enhancement techniques by surface modification and incorporating additives such as nanofluids.

- There is a need to develop generalized models for predicting heat transfer coefficient for large surfaces and to investigate heat transfer enhancement techniques by surface modification and incorporating additives such as nanofluids.
- Surface engineering-enhanced spray cooling is efficient in numerous cooling applications, especially at high heat fluxes with low coolant flow rates. The main spray cooling enhancement mechanisms are improved wickability, triple contact line length, active nucleation sites, and flow confinement for nanostructured surfaces, and increased surface area, flow confinement, and triple contact line length for macrostructured surfaces.
- Spray cooling has critical heat flux (CHF) and heat transfer coefficient (HTC) of 100–1000 W/cm^2 and 1–100 W/cm^{2}K, respectively. These values meet present power electronic cooling demands and are promising for next-generation demands.

In the future, research can be performed on using nano and organic materials. In addition, future researches should be focused on new generation optimization algorithms, economic and CFD analyses [167]. There is a scope to study surface designs that incorporate improvement methods at multiple length scales while considering durability, integration of various components, miniaturization, rapid & smart environmental responses and scalability.

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