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Spray Impingement Cooling: The State of the Art

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Abstract

The cooling of a surface can be achieved by the impingement of spray, which is a free surface flow of droplets ejected from a spray nozzle. Spray cooling can provide uniform cooling and handle high heat fluxes in both single phase and two phases. In this chapter, spray cooling is reviewed from two aspects: the entire spray (spray level) and droplets (droplet level). The discussion on the spray level is focused on the spray cooling performance as a function of fluid properties, flow conditions, surface conditions, and nozzle positioning. The advantages and barriers of using spray cooling for engineering applications are summarized. The discussion on the droplet level is focused on the impact of droplet flow on film flow, which is the key flow mechanism in spray cooling. Droplet flow involves single droplet, droplet train (continuously droplets broke up from jet flow), and droplet burst (droplet groups affecting at a constant frequency), and local cooling enhancement due to droplet flow is discussed in details. Future work and unresolved issues in spray cooling are proposed.

Keywords: spray cooling, spray property, enhanced surface, droplet train, droplet burst, flowing film

1. Introduction

Thermal management becomes increasingly important and challenging as the increase of power/heat density is taking place in many engineering applications, products, and industrial sectors. One example is the electronics industry. Advances in semiconductor manufacturing technology create more compact integrated circuits for electric devices. The latest Fin Field Effect Transistor (FinFET) technology contributes to the reduction of fabrication node from 22 nm in the year of 2012 to the current 10 nm, and even to 5 nm in 2021. Using a 10 nm FinFET manufacturing process, Apple A11 chip could contain 4.3 billion transistors on a die of

~87 mm², which is 30% smaller than the last version A10. In addition, thermal design power of electric chips, the maximum amount of heat removal from the electric chips, shows an increasing trend. As heat power density continues to grow, heat removal, also referred to as thermal management, is important for maintaining the temperature to meet material and safety constraints. In turn, the development and maintenance of electric devices rely on how effectively the heat is dissipated from the devices. The choice of cooling technology is a complicated systems work in high-power electronic, not only for fitting in the heat removal requirement from low power density to high power density, but also for considering the cooling efficiency, power load, overall power consumption of the cooling subsystem, and the cost of cooling infrastructure. This chapter focuses on fundamental heat removal capacities of cooling technology.

Different cooling technologies vary in their heat removal capacities, which are summarized in **Figure 1**. For low heat flux removal requirement, air-cooling, which removes the heat from the hot surface by airflow, is widely applied. The cooling performance can be enhanced by expanding the surface area or increasing the flow of air over the surface. The first approach is known as air free convection, while the second approach is air-forced convection. In comparison with free convection, the fluid motion in forced convection is generated by external source, for enhancing the local convection. In computers, cooling fins are added to heat sink for expanding the surface area, while a fan is attached to the cooling fins to enhance air convection. Heat flux by forced air convection can reach ~35 W/cm² while only ~15 W/cm² by free air convection (see **Figure 1**). Due to the increase of power density, many micro-electronic and power electronic devices now are in the range of heat flux beyond the air cooling capacity. Effective liquid cooling solutions are needed for thermal management of the high-heat-flux devices.

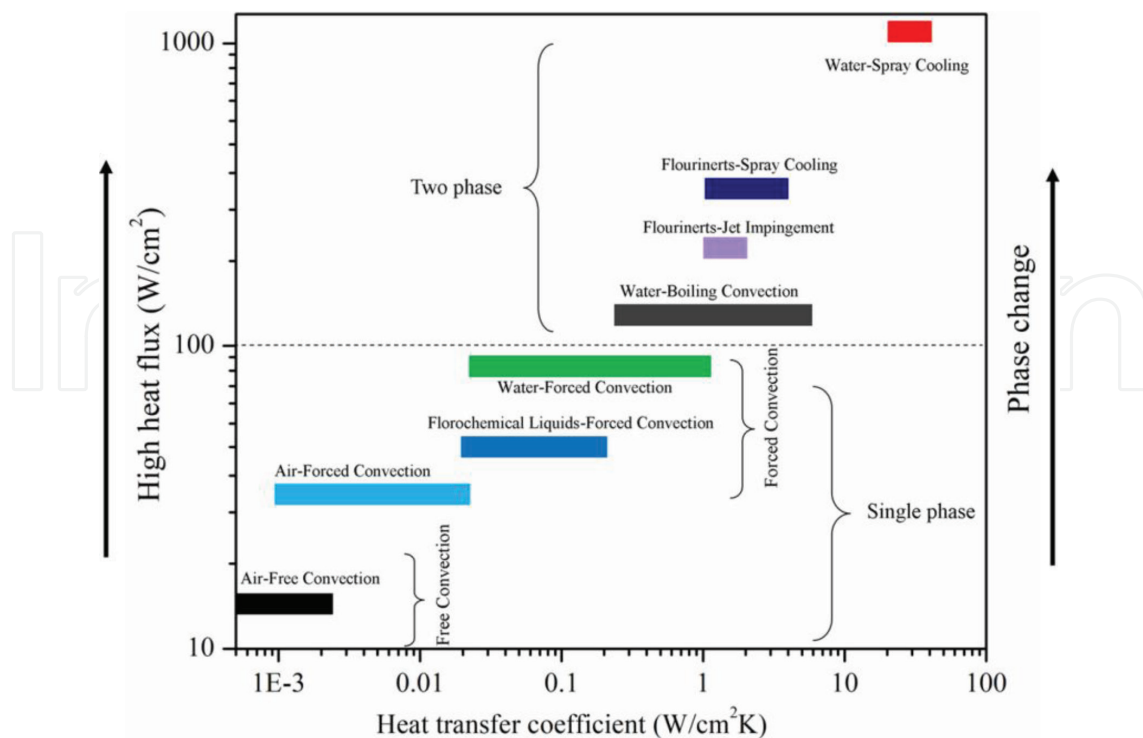


Figure 1. Heat removal capacity by applying different cooling technologies that is characterized by two parameters: Highest heat flux and heat transfer coefficient [1–4].

Spray cooling is one effective solution, which has the huge potential in handling the high heat fluxes in high-power electronics such as supercomputer, lasers, and radars. Spray cooling has several advantages over other cooling techniques. In comparison with air-cooling and jet impingement cooling, spray cooling owns a high heat flux removal capacity. Spray cooling can transfer heat in excess of 100 W/cm^2 using fluorinerts and more than 1000 W/cm^2 using water (see **Figure 1**). Due to high heat flux removal capacity, spray cooling allows precise temperature control with low fluid inventory [5]. Besides, spray cooling has uniform cooling temperature distribution over the entire spray-covered surface. This is because the entire spray-cooled area is receiving fresh liquid coolant droplets. For jet impingement cooling, the coolant flows radially outwards from the impingement spot. The radial flow has non-uniform temperature, and the largest subcooling and the optimal local cooling occur at the stagnation point. The non-uniform cooling results in non-uniform surface temperature in the cooling area, which could be significant for high heat fluxes.

However, there are still some barriers for applying spray cooling for engineering applications. Significant pumping power is needed to achieve large pressure drop through spray nozzle to produce fine spray, but the low cost is first priority in commercial application of cooling technologies. Another fact that the design and fabrication of spray nozzle do not follow the identical industry standard makes the unpredictable spray characterization. Hence, it is hard to get a universal correlation of spray characterization to cooling performance, which also limits the implementation of spray cooling. Additionally, in comparison with the jet nozzle, nozzle orifice through the spray coolant is even smaller, increasing the possibility of orifice clogging and the occurrence of the dry-out area on the heated surface [6]. In spite of these barriers, spray cooling is still a popular cooling technology and many successful applications were reported for supercomputer (CRAY X-1) [7], laser diode laser arrays [8], microwave source components [9] and NASA's reduced gravity aircraft [10].

In spray cooling, liquid coolant is emitted from a pressurized nozzle and breaks up into numerous droplets. The small droplets land on the cooled surface, where the flow of droplets becomes a thin liquid film radially flowing on the surface (see **Figure 2a**). The cooling is achieved through the convection heat transfer from the cooled surface to the film flow being impacted by continuous flow of droplets, nucleate boiling on the cooled surface, liquid conduction inside the film flow, and interfacial evaporation from the liquid film to the surrounding air. Spray cooling provides uniform cooling that can handle high heat fluxes in both single phase and two phases. The cooling performance as a function of spray characterization, flow conditions, surface conditions, and nozzle positioning was widely discussed in past decades. These studies focused on the relationship between the spray cooling performance and the entire spray flow. However, in these spray-level studies, the understanding of cooling mechanism of spray droplets is missing. At the droplet level, the impact conditions are classified into a few categories (see **Figure 2b**): (a) impact of single droplet on dry surface appearing in nucleate boiling, transition boiling and film boiling, (b) impact of single droplet on stationary film where the radial velocity of the film is close to zero, such as stagnation zone, (c) impact of single droplet on radially flowing film and (d) impact of droplet burst on flowing film (droplet groups that frequently impact the surface). Although spray impingement cannot be simply considered as the superposition of single droplets due to the interaction of the neighboring droplets [11], the study of local cooling

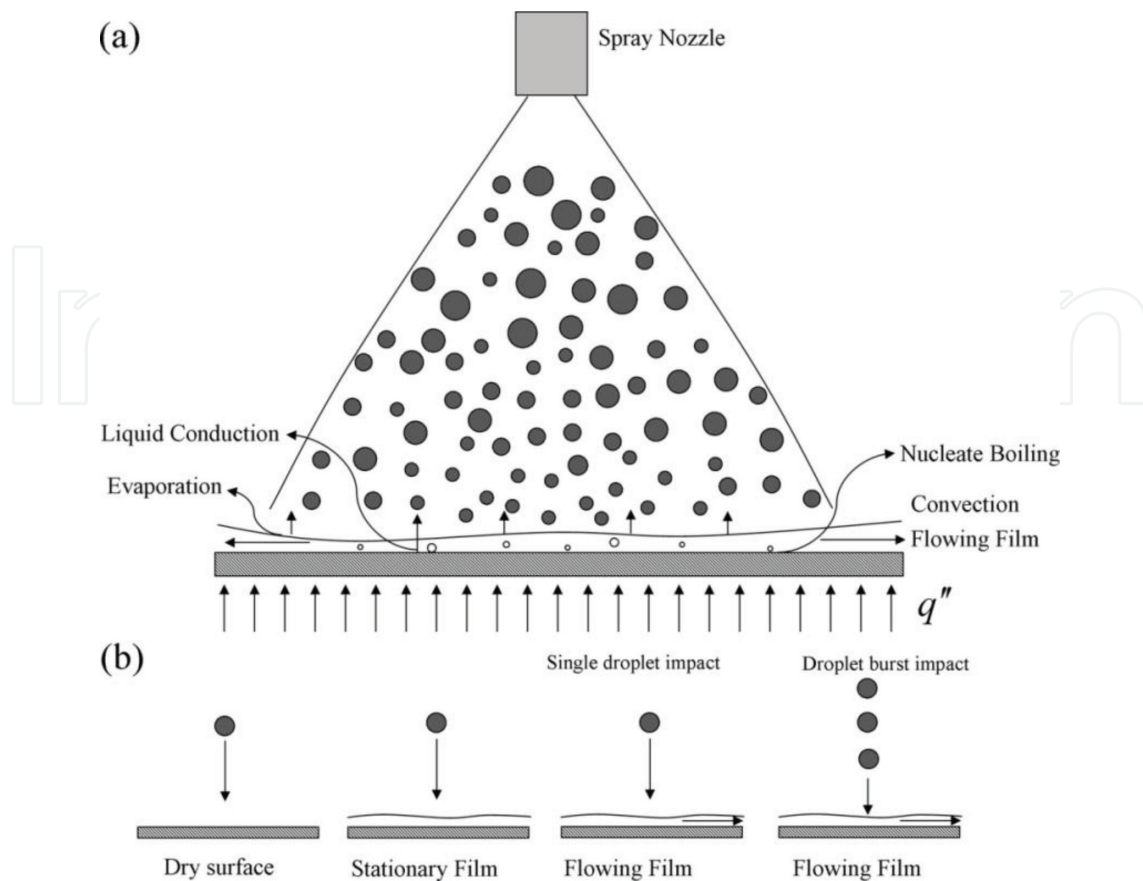


Figure 2. Spray cooling mechanism at the entire spray level (a) and droplet level (b).

performance at droplet level is still significant to the understanding of spray cooling mechanism, especially for the condition of the local film dominated by the droplet flow. Therefore, the research outcomes of spray cooling are reviewed from two aspects: the spray level and the droplet level.

2. Spray cooling at the spray level

Spray cooling can handle high heat flux in the constrictive space of electronic package when comparing to air-cooling, pool cooling, and jet cooling. This is because numerous fresh droplets generated by spray nozzle randomly affect the entire surface, and directly transfer the heat from surface to the coolant. The difference of fluid dynamics between spray impact and other cooling methods is a key factor affecting the mechanism of local heat transfer and resulting in different cooling performance. The first step of studying spray-cooling mechanism is to observe what happened on the heated surface. Numerous fundamental studies have been conducted theoretically and experimentally, which focus on the key parameters affecting impact dynamics and the relevant heat transfer mechanism. There are four aspects that have been demonstrated to significantly affect cooling performance, including spray characterization, nozzle positioning, phase change and enhanced surface [5, 6, 9].

2.1. Spray characterization

Since the earliest study on spray cooling by Toda [12, 13], many researchers put effort on spray characterization, the relevant cooling performance and the critical heat flux (CHF) in spray cooling. Spray characterization mainly involves droplet size, impact velocity, droplet flux, and volumetric flux. However, in experimental studies it is difficult to change only one parameter and isolate the remaining parameters. For example, on the cooled surface the increase of flow rate of coolant spray is accompanied with the increase of impact velocity and volumetric flux with a constant impact area. That is reason that the conclusions made on the dominant impact parameter are not consistent in previous studies of spray cooling.

Chen et al. [14] studied effects of three spray parameters of droplet size, droplet velocity and droplet flux on CHF. By adjusting spray nozzles, operating pressures, and spray distance between the nozzle exit and the heater surface, the effect of one spray parameter was studied while the others were kept constant. It was found that the mean droplet velocity is the most dominant parameter affecting CHF followed by the mean droplet flux, while the Sauter mean droplet diameter (d_{32}) has a negligible effect on CHF. In their later study [15], they further demonstrated the CHF varies with $N^{1/6}$ and $U^{1/4}$ (N and U are referred to as droplet flux and impact velocity). After determining local spray characteristics and local cooling in the water spray boiling curves, Mudawar and Valentine [16] found the dominant effect of the volumetric spray flux as compared to other spray parameters, and CHF was correlated to the volumetric spray flux and mean droplet diameter. After applying the dielectric coolant of PF-5052 with a lower boiling point of 50°C, Rybicki and Mudawar [4] concluded that the volumetric flux and droplet diameter are the most significant spray parameters influencing the spray cooling performance. Heat flux increases with increasing volumetric flux for a number of reasons. A larger fluid volumetric flux results in higher liquid velocity over the surface. The impact of the droplets onto the film can also interact with the liquid film, thinning the local thermal boundary layer.

In single-phase spray cooling, spray droplets land on a radially flowing film. Some researchers studied the property of the flowing film and its relation to spray cooling performance. Pautsch and Shedd [17] used a non-intrusive optical technique to measure the local film thickness generated by sprays. The film thickness was found to remain constant when the heat transfer mechanism was dominated by single-phase convection. Beyond the spray impact area, the dry-out phenomena appear even when the CHF is not reached. In the nucleate boiling regime, Horacek et al. [18, 19] measured the dry-out area, which was characterized by the three-phase contact line length, and measured using a Total Internal Reflectance technique. The wall heat flux was found to correlate very well with the contact line length. This contact line heat transfer mechanism was summarized by Kim [20] as one of main heat transfer mechanisms in the two-phase regime.

2.2. Nozzle positioning

Cooling performance can be influenced by changing the spray positioning. There are two significant positioning parameters in the study of spray cooling (see **Figure 3**): nozzle-surface distance H (the distance from the nozzle tip to the impact surface), and inclination angle θ (angle between spray axis and the surface normal). Geometrically, the spray impact on a

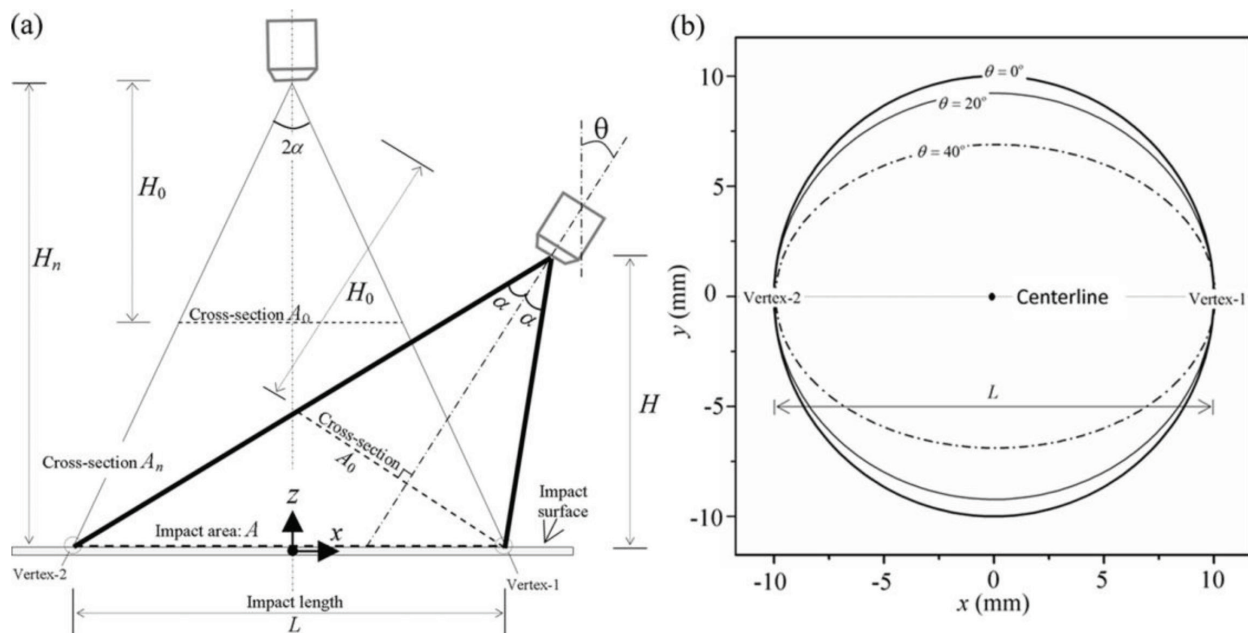


Figure 3. (a) The 2D geometry is on the central plane (z-x plane) of the cone perpendicular to the impacted surface (x-y plane). The positioning of the nozzle is determined by inclination angle θ and spray height H . H_n is the required spray height by normal impact to cover a given impact length L . (b) Impact area with constant impact length L formed by the spray inclined at different angles θ [21].

surface is a spray cone intersected by the impact surface. In normal spray impact changing nozzle-surface distance causes the change of spray covered area (see impact length L in Figure 3a), the local volumetric flux and film flow and relevant local cooling. Within the small surface area around 1 cm^2 , Mudawar and Estes [22] found that the optimal nozzle-surface distance for the maximum CHF is achieved when the spray footprint is exactly enclosed within the cooling surface. Recently, in a larger surface area around 5.5 cm^2 the optimal spray height for the largest area-averaged heat transfer coefficient was found to be smaller than that required for covering the entire heater area [21]. The reason is that the maximum local cooling appears at the edge of the impact, and the film flow outside the impact area still provides the effective cooling. However, this phenomenon is not significant in small heated area.

Some researchers focus on the effects of spray inclination on heat transfer performance. The impact area is circular for normal impact $\theta = 0^\circ$, and elliptical for inclined spray impact $0^\circ < \theta < (90^\circ - \alpha)$. The inclination angle is limited within $90^\circ - \alpha$. Otherwise, no spray lands on the cooled substrate. In experimental tests, the impact area, surface area and heater area are usually concentric, and the center is located at $(x, y) = (0, 0)$ (see Figure 3b). Besides, impact length L maintains the same for studying the inclination influence on the cooling. Silk et al. [23] compared the cooling performance of three-inclination impact to normal impact on enhanced surface. It was found on both the flat surface and enhanced surface that heat flux increases with the increase of spray angle up to $\theta = 15^\circ$. However, when $\theta > 15^\circ$ the heat flux performance is little changed within the experimental uncertainty. Cooling enhancement by inclined spray is attributed to better liquid drainage through the elimination of the stagnation zone, which appears at the center in normal spray impact. Wang et al. [24] found that inclination of spray nozzle could enhance heat transfer if optimal orifice-surface distance is found. However, Visaria and Mudawar [25] indicated that inclination angle has minimal impact on the single-phase or two-phase regions of the boiling curve. Increasing

inclination angle even decreases CHF and maximum CHF is always attained with the spray normal to the cooled surface. Rybicki and Mudawar [4] used upward-oriented and downward-oriented spray nozzles to assess their effects on cooling performance. The experimental results showed that the spray orientation has no measurable effects on the global cooling performance in both single-phase and two-phase regimes. Cheng et al. [26] found that the inclination angle would worsen heat transfer when the spray footprint is smaller than the heated surface. Therefore, the conclusions of these studies on spray inclination are contradictory.

There are three reasons addressed for contradictory conclusion of spray inclination. One is regarding the different nozzle positioning. As illustrated in **Figure 3**, two key parameters, spray distance and inclination angle, determine the nozzle positioning. However, at a certain inclination angle some studies [23] applied the constant spray distance, while others [4, 24, 25] adjusted the distance for the constant impact length. Another reason is related to the assumption of one dimensional steady-state conduction through the neck of cartridge heater for the surface heat flux calculation. Inclined spray impact causes considerable temperature difference on the cooled surface (see **Figure 4**). Hence, the radial conduction should be taken into account for inclined spray cooling. The last reason is from the surface temperature

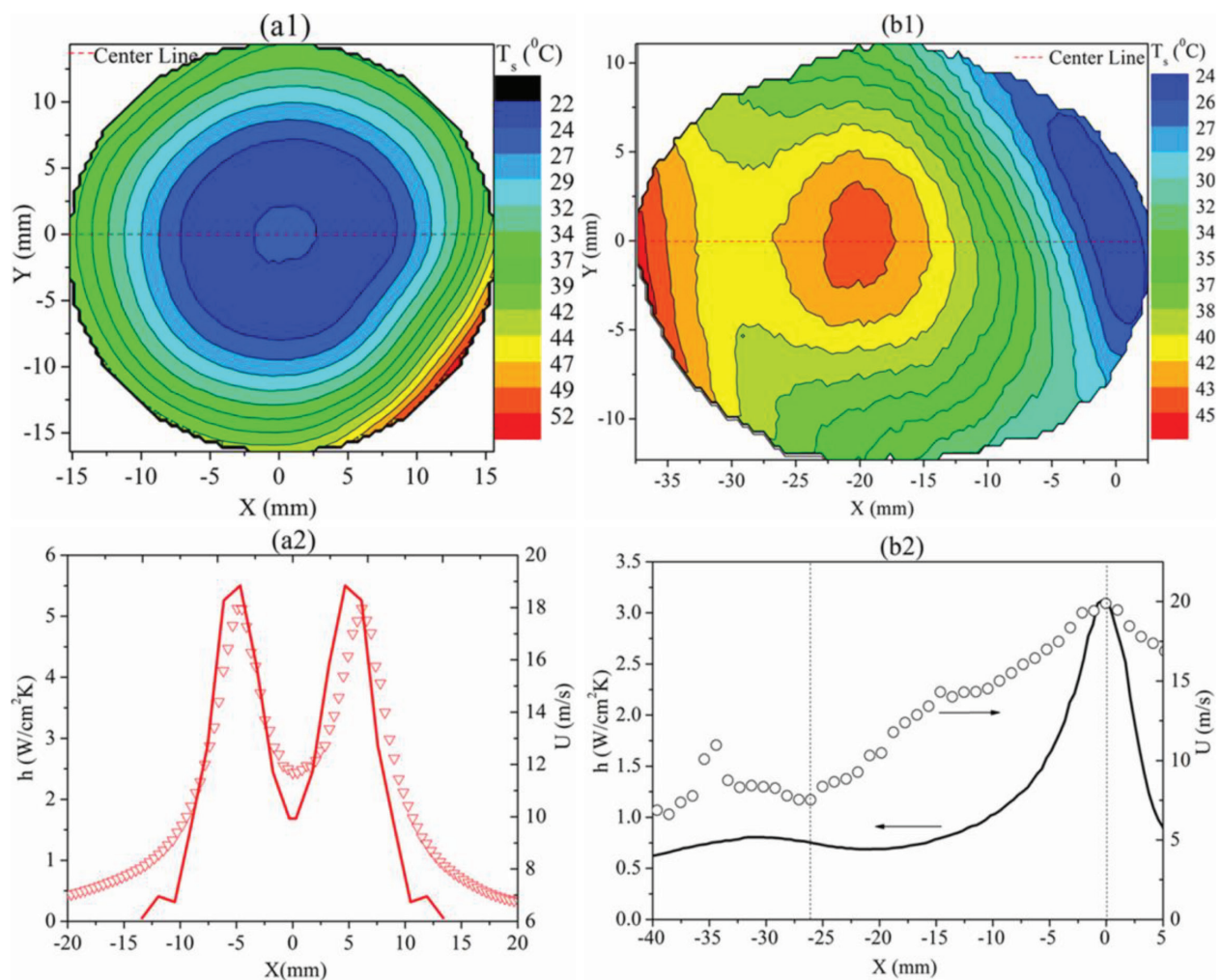


Figure 4. Local surface temperature distribution for normal impact (a1) and inclination affect with $\theta = 30^\circ$ (b1). Local droplet velocity and the relevant local heat transfer coefficient are plotted along the centerline in (a2) and (b2) [27].

measurement location. Different radial locations provide different temperature measurement due to significant temperature difference in inclined spray cooling.

To obtain surface temperature distribution in inclined spray, some researchers investigated local heat transfer by replacing cartridge heater with sputter-coated thin film heater, which enables infrared thermography for temperature measurement [21, 27, 28]. All of these studies found significant temperature difference on cooled surface for inclined spray cooling (one example in **Figure 4b1**). Gao and Li [27] compared the droplet impact velocity and heat transfer coefficient distribution along centerline for normal impact and inclined spray impact (see **Figure 4a2** and **b2**). The impact velocity was captured by a Stereo-Particle Imaging Velocimetry system. The trend line of heat transfer coefficient and droplet velocity shows clear correlation. For both cases, the locations of maximum droplet velocity coincide with the locations of the highest heat transfer coefficient. The further study by Gao and Li [21] indicated the global cooling shows slight diminishment for small inclination angle and enhancement for large inclination angles. On the central plane of the spray cone, the enhancement and diminishment of the local cooling performance are in general agreement with the increase and decrease of the spray flux. Thin film heater is not reliable for the surface temperature greater than boiling point, and experiments are tested in single-phase region. This is the limitation of thin film heater, and the robust heater for boiling test is needed for future study.

2.3. Phase change in spray cooling

Similar to pool boiling curve, the heat transfer curve of spray cooling can be separated to four regimes: single phase regime, nucleate boiling regime, transition boiling regime and film boiling regime [12, 13]. In the single phase regime, the heat flux linearly increases with increasing surface temperature difference between heater surface and coolant. Forced convection by radially moving film and evaporation on unsteady interface of thin film layer, play dominant roles in single-phase regime [29]. In the nucleate boiling regime, bubbles begin to repeatedly occur at nucleation sites on the heated surface, and the heat flux sharply increases as compared to single-phase cooling. Once the nucleation sites cover the heated surface completely, average heat flux will reach a peak value, which is defined as Critical Heat Flux (CHF).

Once reaching the CHF and coming to the transition boiling (decreasing region in the boiling curve), the efficiency of heat transfer on the heating surface significantly decreases. Liquid coolant absorbs heat from the surface and forms the vapor blanket, so the surrounding liquids are hard to get to the heater surface. That is the reason for the sharp decrease of heat flux in this regime. In the film, boiling regime an interesting phenomenon is an increasing trend of heat flux. Massive heat is generated from the heated surface and radiation heat transfer becomes a key heat transfer mechanism between the heated surface and the liquid, so the heat flux tends to increase from the Leidenfrost point. Considering the safety limit and fast implementation of electronic cooling, researchers' attention is paid to the theoretical correlation in single phase regime and nucleation boiling regime.

In the single phase regime, Rybicki and Mudawar [4] proposed the correlation for dielectric PF-5050 spray, which is

$$Nu = 4.7 Re^{0.61} Pr^{0.32} \quad (1)$$

Here Nu is the Nusselt number, Re is the Reynolds number, and Pr is the Prandtl number. Karwa et al. [30] developed a heat transfer correlation for full-cone water sprays, which is

$$Nu = 20.344 Re^{0.659} \quad (2)$$

The correlation has an accuracy of $\pm 7.3\%$ for varied pressure drops. Heieh and Tien [29] studied R-134a spray cooling, and correlated the Nusselt number to the Weber number, size distribution and sensible heat effects in the single phase regime, which is

$$Nu = 933 We^{0.36} (d_{32}/d_0)^{0.25} (\Delta T/T_s)^{0.027} \quad (3)$$

In the nucleate boiling regime of spray cooling, the heat flux increases with the surface temperature faster than that in single-phase regime. Yang et al. [31] proposed two reasons. In nucleation, boiling bubble appears and grows on nucleation sites as the liquid coolant changes to the vapor. During the phase change, a larger amount of heat is removed from the heated surface, resulting in a temperature drop on nucleation sites. The other reason is attributed to the influence of secondary nucleation and evaporation on the heat flux enhancement [32]. When the numerous droplets impinge on heated surface, air is entrained into the liquid film, forming an air layer underneath the droplets. The air layer reaches the liquid-covered surface and finally breaks up into many tiny gas nuclei, which serve as secondary nucleation sites. Hence, the number of secondary nucleation sites is proportional to the droplet flux across the surface, which was proved in Yang's experiments [33]. Using water as coolant liquid, Mudawar and Valentine [16] proposed the CHF correlation with respect to the local volumetric flux Q'' , and Sauter mean diameter (SMD) d_{32} :

$$\frac{q_m'}{\rho_s Q'' h_{fg}} = f \left(\frac{\rho_f}{\rho_s}, \frac{\rho_f Q''^2 d_{32}}{\sigma}, \frac{\rho_f c_{pf} \Delta T_{sub}}{\rho_s h_{fg}} \right) \quad (4)$$

In another study by Estes and Mudawar [34], a universal CHF correlation was constructed for spray cooling by using Fluorinerts FC-72 and FC-87 as well as the water.

$$\frac{q_m'}{\rho_s Q'' h_{fg}} = 2.3 \left(\frac{\rho_f}{\rho_s} \right)^{0.3} \left(\frac{\rho_f Q''^2 d_{32}}{\sigma} \right)^{-0.35} \left(1 + 0.0019 \frac{\rho_f c_{pf} \Delta T_{sub}}{\rho_s h_{fg}} \right) \quad (5)$$

2.4. Enhanced surfaces

Enhancing spray cooling by changing the surface structure is one effective and low-cost approach, which benefits from optimal liquid management and enhancement of local cooling efficiency. According to the structure size, enhanced surface is classified into four categories: mini-structured surface, micro-structured surface, nano-structured surface, and hybrid-structured surface. Most of early studies of spray cooling have been conducted on flat surfaces. A few of them focus on the effects of surface roughness on cooling enhancement. Pais et al. [35] fabricated three rough surfaces using polishing grit with the size range of 0.3–22 μm and examined the roughness influence on heat removal capabilities. Tests showed that as the surface roughness decreases the CHF increases. CHF is up to 1200 W/cm² on the surface by

polishing grit of $0.3\ \mu\text{m}$ while only $1000\ \text{W}/\text{cm}^2$ on the surface by $22\ \mu\text{m}$ grit. This is because the large surface roughness implies a thicker film thickness, leading to the later bubble breakup and departure, the impeding of vapor escape, the increased resistance to heat flux through evaporation on film surface, and the dampening of droplet impingement.

Mini-textured surfaces feature structure size above $1\ \text{mm}$, and the structure types of cubic pin fins, pyramids, and straight fins and so on (see **Figure 5a**). Silk et al. [23] observed that addition of finned structure to cooled surface decreases the convective thermal resistance, and increases the convection heat transfer relative to the flat surface, since the total wetted surface area is larger on the enhanced surface. Although the cubic pin fins and straight fins have the same wetted surface area, cooling performance of straight fins surface exceeds that of the cubic pin fins surface. This is attributed to liquid management on the heated surface and cooling efficiency on the wetted surface area. Xie et al. [39] indicated that the fin arrangement is a dominant factor in enhancing heat transfer rather than the wetted surface area. The improper fin arrangement causes the thick and slow moving liquid film and thus worsens the local cooling performance. This point of view needs further validation by measuring the change of local surface temperature.

Micro/nano or hybrid structured surfaces have been attracted huge attention to spray cooling as micro fabrication technology advances new micro-/nano-engineered surface in the last decade (see **Figure 5 b, c, d**). The experimental studies [36, 39–41] applied micro-textured surfaces with surface feature size from 25 to $480\ \mu\text{m}$, which is close to liquid film thickness but larger than average droplet size. Micro-textured surfaces showed slight effect on heat transfer enhancement in the flooded region, but greatly enhancing cooling performance in the thin film and partial dry-out regions as compared to the flat surface. The study by Zhang et al. [37] showed that nanostructured surface has better cooling performance since the contact angle is

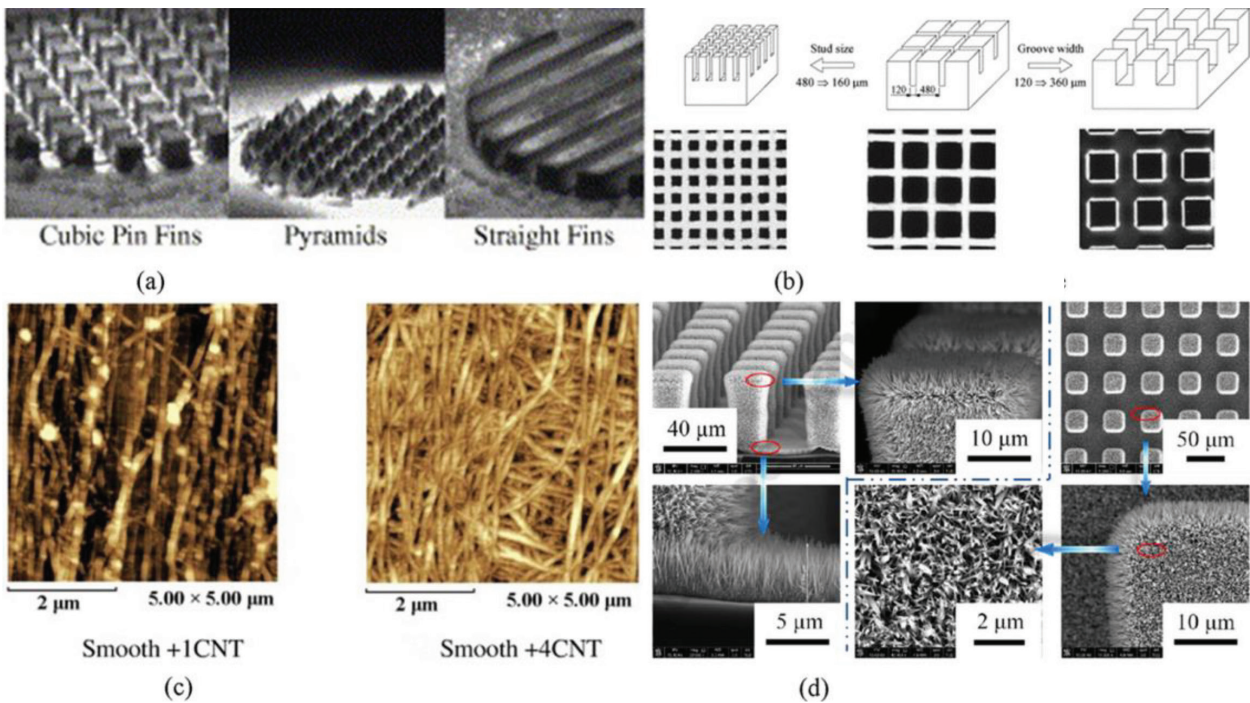


Figure 5. (a) Millimetric structured surface [23], (b) micro-structured surface [36], (c) Nano-structured surface [37], (d) hybrid micro/nano structured surface [38].

smallest on the nanostructured surface as compared to micro-structured surfaces and flat surfaces. Recently, Chen et al. [38] developed a hybrid micro/nano structured surface by growing the ZnO nanowire arrays on the top of etched micro-structured silicon wafer. Test results showed that cooling performance of hybrid surface is better than the micro-structured surface in boiling regime because of its great wetting capacity and reduction in dry-out surface area. If comparing performance of nanostructured surface [37] and hybrid surface [38], there is no significant difference in heat flux enhancement relative to the smooth surface.

3. Spray cooling at the droplet level

The impact dynamics during spray cooling is complicated as it involves many liquid phenomena, such as spreading, receding, splashing, droplet collision, generation of stationary film and radially flowing film, and liquid flooding. All of these impact phenomena result from the interaction of droplet flow and film flow on the impact surface. Droplet flow includes three types: single droplet, droplet train (continuous droplets formed from jet breakup), and droplet burst (portion of droplet train selected at a certain frequency). Similarly, film flow conditions involve dry surface (no film), stationary film, radially flowing film, or their combination on the cooling surface (see **Figure 6**).

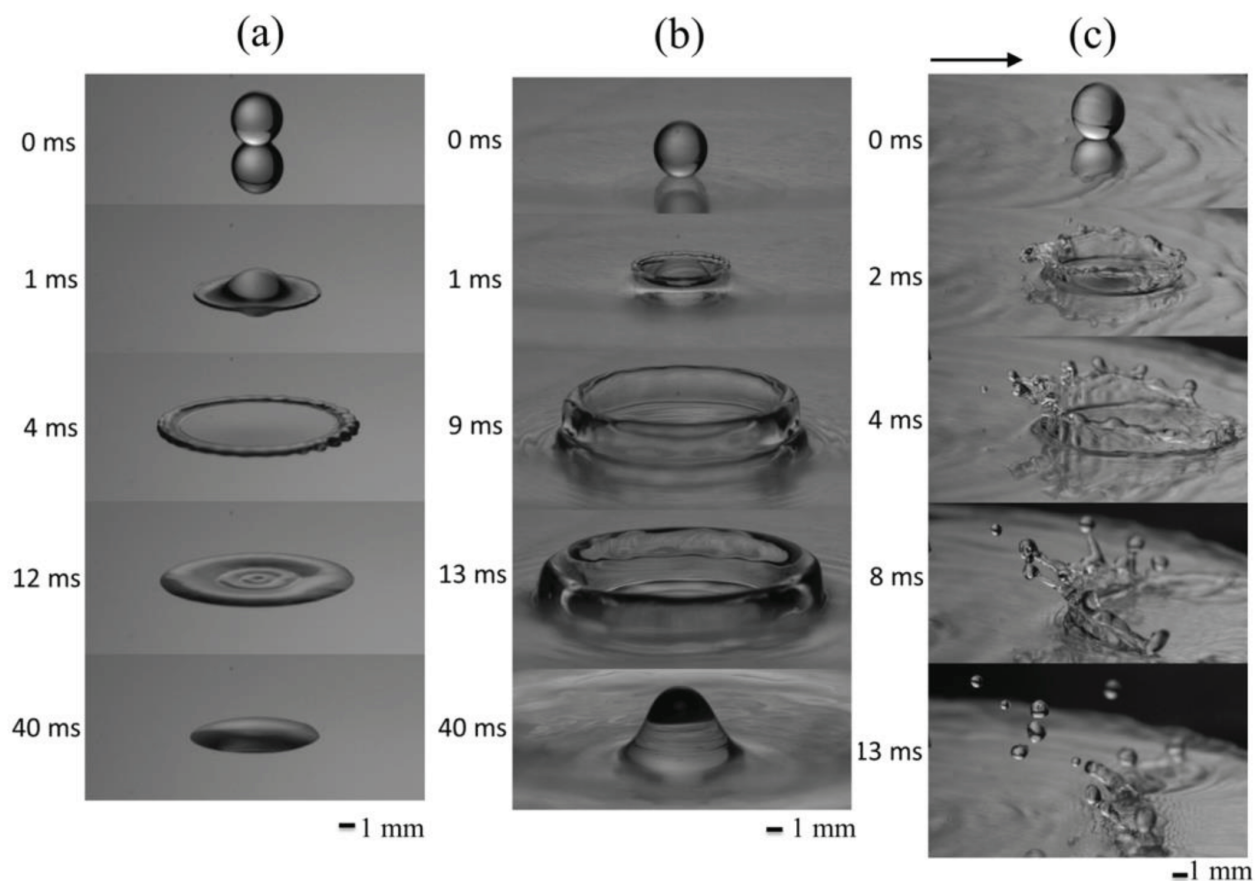


Figure 6. Single water droplets with same velocity and diameter ($U_0 = 1.85$ m/s, $D_0 = 3.2$ mm) impact three different surface conditions: (a) dry surface, (b) stationary water film, (c) flowing water film [42].

The droplet and film flow conditions are two flow parameters directly determining the heat transfer mechanism of spray cooling. Coolant droplets bring significant temperature difference between the expanding droplet flow and flowing film, which contributes to the reduction of thermal resistance inside the film layer and enhancement of heat transfer from the heated surface to the flowing flow. Fluid dynamics on the impact surface is responsible for the local convection heat transfer. The fast flowing film transfers more heat to downstream. Thin film thickness reduces the thermal boundary layer and encourages evaporation from the liquid interface. Therefore, the fluid dynamics study of droplet affecting film enables us to get insight into thermal results of droplet impact on the film-cooled hot surface, and further understand spray cooling performance. The relevant literature is reviewed based on the droplet flow condition: single droplet impact, droplet train impact, and droplet burst impact.

3.1. Single droplet impact cooling

3.1.1. Impact on dry surfaces

The dry surface usually appears in two-phase spray cooling, which is shown by the change of contact line length. The researchers reported that the critical heat flux in spray cooling is achieved at the greatest contact line length. On dry surface, droplet impact dynamics on droplet-covered surface area is essential to local cooling performance. The process of a liquid droplet impact was divided by Rioboo et al. [43] into five successive phases: kinematic, spreading, relaxation, wetting, and equilibrium. Most research work has been focused on spreading and relaxation. In the spreading phase, contact line expands radially until reaching a maximum spreading, which is determined by droplet initial diameter, impact velocity, surface tension, viscosity, and wettability of the solid surface (Li et al. [44]). The maximum spread diameter is of critical importance in spreading phase. Clanet et al. [45] found that on a super-hydrophobic surface the maximal spread is significantly dependent on the viscosity of liquid droplets and scales as a function of Weber number $\sim We^{1/4}$. van Dam and Clerc [46] found a significant difference of maximum spread between substrates with small and large contact angles, showing the significant influence of wettability in the later stage of impact. A lower air pressure was found to suppress the droplet spreading, leading to a smaller maximum spread [47].

Some analytical models were proposed to predict impact process, most of which were based on the energy conservation of the impact droplet. Chandra and Avedisian [48] developed an empirical correlation of viscous dissipation, including estimated spreading time, simplified dissipation function, and estimated volume of viscous dissipation. Gao and Li [49] proposed a theoretical model based on the actual dynamic shape of the droplet that could successfully predict the maximum spreading diameter and receding diameter during the recoiling process. Some of the researchers put efforts on the investigation of splash using varied dry surfaces. Surface roughness and textures were demonstrated to influence the splash limit [50, 51]. Droplet impact on a moving surface was found to show different splash and non-splash phenomena as compared to stationary surfaces [52]. Previous studies on splash threshold under different surface conditions are summarized in **Table 1**.

Surface conditions	Threshold parameter K	Critical value K_c	References
Dry surface	$(WeRe^{1/2})^{1/2}$	57.7	Mundo et al. [50]
	$We^{0.5}Re^{-0.391}$	0.8458	Vander Wal et al. [53]
Moving dry surface	$WeRe^{1/2}(1-2.5\frac{U}{U_0}Re^{-1/2})^2$	5700	Bird et al. [52]
Stationary liquid film	$(WeRe^{1/2})^{0.8}$	2100	Cossali et al. [54]
	$We^{0.5}Re^{0.17}$	63	Vander Wal et al. [53]
Flowing liquid film	$WeRe^{1/2}(1+\bar{h}_f\bar{U}_f^2)(1+\bar{h}_f\bar{U}_f)^{1/2}$	3378	Gao and Li [42]

Table 1. Summary of splash thresholds under different surface conditions [42].

On heated dry surface, Bernardin et al. [55] mapped the boiling curve of droplet impact cooling as the same as the spray cooling. In the regime of single-phase liquid cooling, Pasandideh-Fard et al. [56] observed that increasing impact velocity would enhance heat flux around the impact area. This is because the raising droplet velocity promotes droplet spreading, thus increasing the wetted area on the heated substrate. However, increasing droplet impact velocity slightly enhances heat flux at the impact point. Batzdorf et al. [57] proposed a theoretical mode to predict the heat transfer rate during the droplet impact. The theoretical prediction is more accurate when the liquid Prandtl number $Pr>5$, since the droplet evaporation is not taken into account in the model. The predicted heat transfer rate shows a quick increase to the peak value and then the slow decreasing.

On superheated surface with temperature over 200°C, Tran et al. [58] found three significant phenomena after droplet impact: contact boiling (droplet contacts with the surface), film boiling (vapor layer formed underneath the droplet), and spray film boiling (vapor layer and tiny droplets ejected upward) (see **Figure 7a**). Their experiments showed that the maximum spreading of a droplet impact follows a universal scaling with the Weber number ($\sim We^{2/5}$), which is steeper than that on nonheated surface ($\sim We^{1/4}$) [45]. The steeper curve on heated surface results from a driving mechanism, which is caused by the evaporating vapor radially expanding and pushing liquid outward. Staat et al. [59] indicated that the Leidenfrost transition temperature shows little dependence on the Weber number of affecting droplet, but the transition to splashing shows a strong dependence on the surface temperature. Adera et al. [60] reported the formation of non-wetting droplets on a super-hydrophilic micro-structured surface by slightly heating the surface above the saturation temperature of the droplet fluid, which is contributed by the increased thermal conductivity and decreased vapor permeability of the structured region. In experimental study of Jung et al. [61], the transient temperature distribution during droplet spread was detected using infrared thermography. In contact boiling, the droplet coolant contacts the surface and the maximum heat flux is quick to reach at early impact stage ~ 2 ms at impact point. In film boiling, non-wetting surface appears at the early impact, and the maximum heat flux is even lower than that in contact boiling due to the existence of vapor layer underneath the droplet. On heated surface, the study of simultaneous impact of multiple droplets is few, which needs further discussion of droplet collision influence on contact line and local evaporation. This benefits the understanding of two-phase spray cooling and optimization of cooling efficiency.

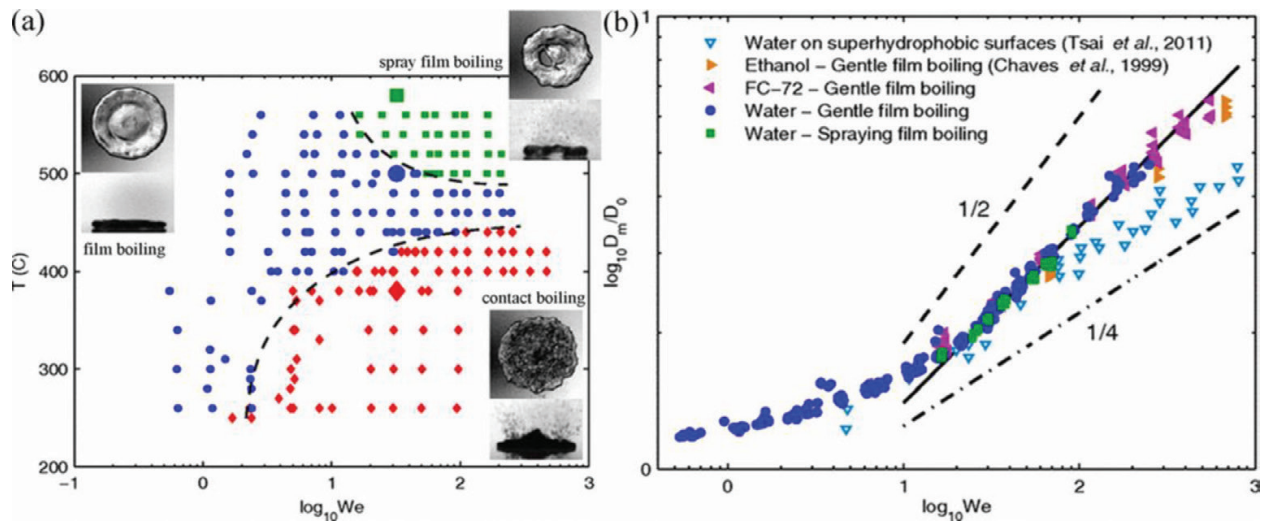


Figure 7. (a) Phase diagram of water droplet impact on a superheated surface [58], (b) plot of the maximum spreading diameter versus weber number [58].

3.1.2. Impact on stationary films

Stationary film occurs in the center of normal spray impact, or locates where the spray nozzle axis intersects with the impact surface in inclined spray (see **Figure 2**). On a stationary film, most researchers focused on spread process and splash formation mechanism after impact. Yarin and Weiss [62] developed a quasi-one-dimensional model, which predicts the existence of a kinematic discontinuity in the velocity and film thickness distribution. The discontinuity corresponds to the emergence of an uprising liquid sheet. Roisman and Tropea [63] generalized Yarin's theory for the case of arbitrary velocity vectors in the liquid films both inside and outside the crown. Yarin and Weiss [62] experimentally found the crown radius from the impact center could be expressed as a function of the non-dimensional spreading time. Two empirical parameters existing in their model was given by the later study of Cossali et al. [64]. Droplet impact on a stationary film may or may not result in the splash. Finding the threshold condition for splash impact has been the focus of a few experimental studies. Cossali et al. [64] tested drops of various mixtures of water and glycerol affecting a thin liquid film and proposed an empirical parameter for predicting the occurrence of splash impact. For thick films, Cossali et al. [54] and Rioboo et al. [65] found a critical value of the threshold parameter, i.e. $\kappa_c = 2100$, above which splash impact occurs (see **Table 1**). To the authors' acknowledge few study has been conducted on heat transfer of single droplet impact on heated stationary film. For very thick stationary film, it likes a pool and the relevant heat transfer mechanism can be found in the study of pool boiling.

3.1.3. Impact on flowing films

The interaction between droplet flow and film flow is fundamental fluid dynamics in single-phase spray cooling or nucleate boiling (see **Figure 2b**). Impact dynamics was addressed in some researches. Alghoul et al. [66] presented an experimental investigation of a liquid

droplet affecting onto horizontal moving liquid films. An asymmetrical crown shape was observed due to the effect of the moving film. Che et al. [67] demonstrated the on inclined falling flow asymmetrical crown shape is also formed after droplet impact. Gao and Li [42] further analyzed the early evolvement of droplet impact based on experiments and theoretical model (see **Figure 6c**). Once droplet lands on the film, the droplet flow quickly spreads and pushes the liquid outwards, causing the uprising liquid sheets. However, crown sheet is asymmetric owing to the collision mechanism on crown base. At the early stage of droplet impact, the direction of spreading flow is opposite to that of film flow at the upstream of impact point, while their direction is the same at the downstream. Uprising crown sheet may splash, which is dependent of the instability of the sheet rim. The stretching rate of crown sheet is a key factor influencing the rim instability. Analysis was conducted to derive equation of stretching rate, finding that the highest stretching rate appears at the location which droplet spreading flow is right opposite to the film flow, and the location is also the most probable location of splash. The value of splash threshold was provided to estimate whether splash occurs or not. The secondary droplets from splash fly away from the cooled surface, which do not contribute to the cooling performance. In other words, suppression of splash occurrence should benefit cooling enhancement.

The late study of Gao and Li [68, 69] further observed the whole development of droplet impact on flowing film, and demonstrated its relation to the local cooling. The impact process is observed by high-speed video, showing two states: spreading state, replacing state. In spreading state, the droplet flow spreads and gradually slows down until reaching the maximum spread. After that, the droplet flow is pushed towards the downstream and eventually replaced by the film flow. The measured temperature also shows two stages: response stage when the temperature quickly decreases, and recovery stage in which the temperature recovers to the steady state. An enhancement factor was proposed to indicate convection enhancement relative to the steady-state cooling. The peak enhancement is used to consider enhancement influence of impact velocity, droplet size and film flow rate, which is proportional to the square root of the ratio of the droplet flow rate to the film flow rate $\sim (U_0 D_0 / Q)^{1/2}$. However, the conclusion made cannot be directly applied to spray cooling. One reason is that the film flow was generated by external source rather than by droplet flow itself. Another reason is that averaged cooling performance around the impact area was not involved.

3.2. Droplet train impact cooling

One possible phenomenon in spray cooling is that fresh droplets continuously impact the surface at a certain frequency. The droplet flow is defined as the droplet train flow. The fluid dynamics behind this is the interaction of continuous droplet train flow with the flowing film formed on the heated surface. To investigate heat transfer of spray cooling from this aspect, a few studies have been conducted on the heat transfer of continuous droplet train impinging on hot surfaces. Qiu et al. [70] demonstrated surface temperature influence on the impact dynamics. Prior to the steady state, the droplet film spreads on the heated surface, and the surface temperature enhances the spreading rate of the flowing film when the surface temperature is over the boiling point. With the increase of the surface temperature

the steady-state film-wetted area decreases, and eventually maintains constant after the temperature is greater than 190°C . Besides, the temperature also affects the splashing angle (see **Figure 8**). A stable splashing angle marked by red line is established at higher surface temperature greater than 192°C . The later study of Qiu et al. [71] showed that the inclination of the droplet train decreases the splashing angle and increases the averaged secondary droplet size.

Soriano et al. [72] presented an experimental observation of multiple droplet train impingement. Impact spacing between multiple droplet streams would affect spreading and splashing in impact regimes, and the optimal cooling performance was achieved when the film velocity was not disturbed by adjacent droplet streams. Zhang et al. [73, 74] further demonstrated that both impact spacing and impingement pattern significantly affect local and global cooling performance on the hot surface. In comparison with the circular jet impingement cooling, the droplet train impingement achieves a better cooling performance for various impingement patterns. The same conclusion was made when comparing the cooling performance of droplet train and jet impingement on flowing film that cools the hot surface [75]. Through piezoelectric nozzles more groups of jet flow were generated and broke up to droplet train for cooling the hot surface [76], and the maximum heat flux reaches $\sim 170\text{ W/cm}^2$ with the nozzle diameter of $25\text{ }\mu\text{m}$. However, unclear impact dynamics and its relation to local cooling need the further study.

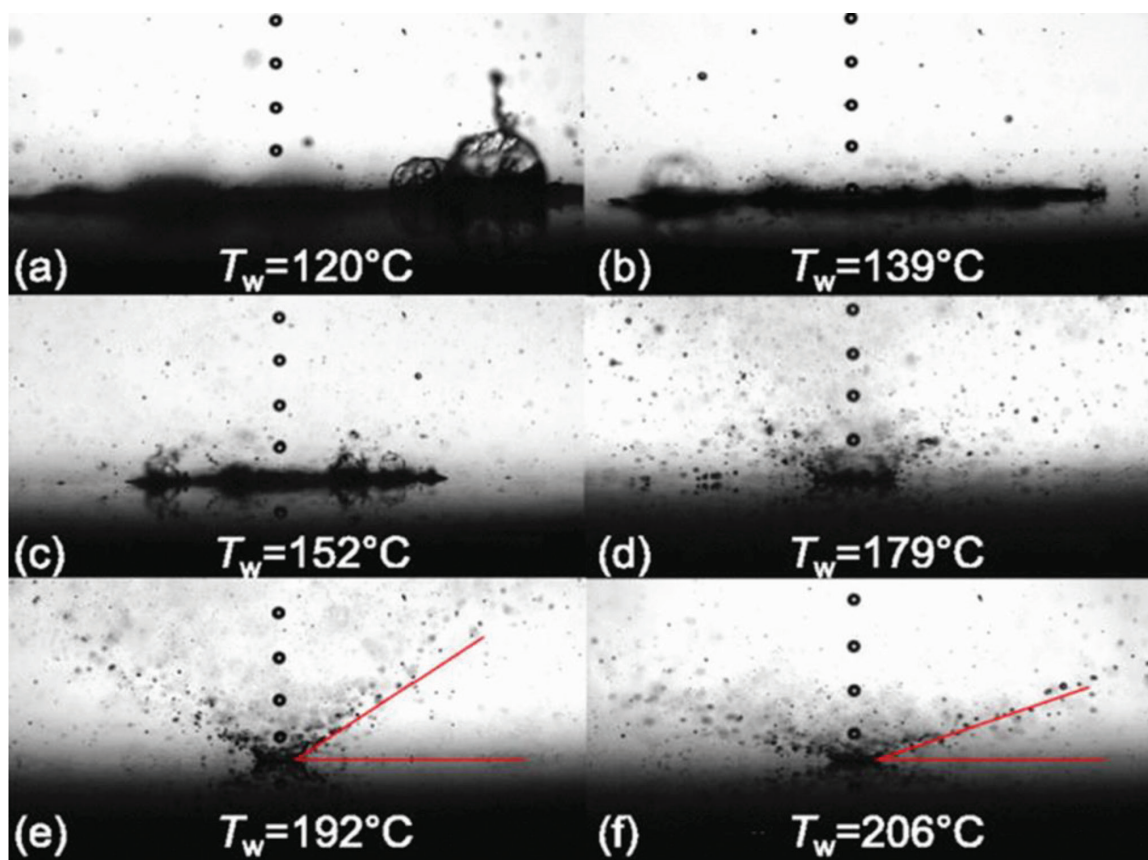


Figure 8. The impact dynamics of droplet train at different surface temperature and the droplet velocity is 15.2 m/s [70].

3.3. Droplet burst impact cooling

Our recent studies try to understand spray cooling from droplet burst aspect [75, 77]. Different from droplet train cooling, it assumed that in spray cooling droplet groups impact the surface at a constant frequency rather than droplet train. Each droplet group is defined as a droplet burst, and each burst contains a constant number of droplets, which is called burst size. The frequency at which droplet bursts are generated is called the burst frequency. The generation mechanism of droplet burst was first proposed by Gao and Li [75, 77] and implemented in tests. A droplet generator combined with controlled interrupter is applied for droplet burst generation. A droplet train is ejected from droplet generator with droplet frequency f_0 , and a circular sector (aluminum plate) with a central angle θ serves as the interrupter. The droplet burst flow is generated by periodically interrupting a droplet train flow into a flow of droplet groups (see **Figure 9**). For each rotating of interrupter, there is only one droplet burst through the interrupter, so that the burst frequency is equal to the rotating frequency of interrupter f_b . The burst size n is determined by the burst frequency and central angle of interrupter $n = f_0 (1 - \theta/2\pi)/f_b$. For example in **Figure 9** (e), $n = 6$ when $f_0 = 1000$ Hz, $f_b = 13.5$ Hz, $\theta = 330^\circ$.

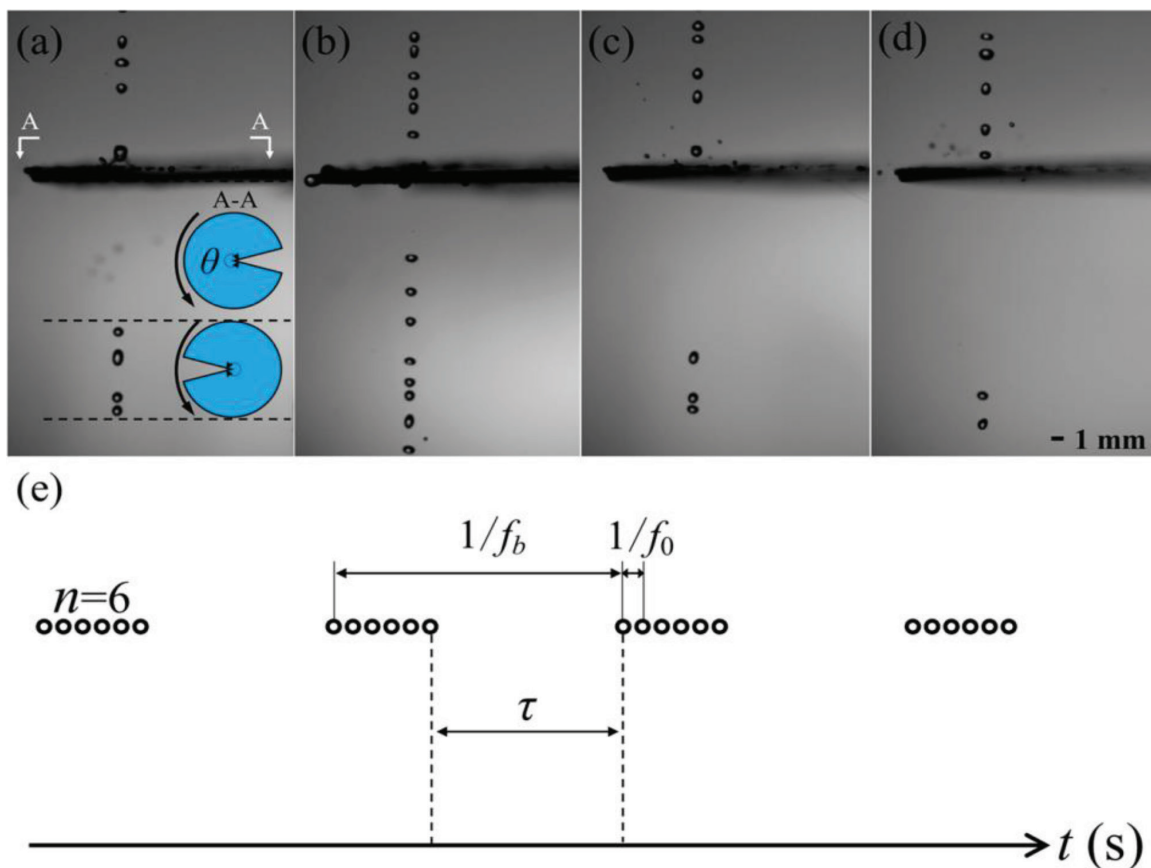


Figure 9. Droplet burst flows are generated by interrupting a droplet train flow ($f_0 = 1000$ Hz) using an interrupter with an angle $\theta = 330^\circ$ and varied frequencies f_b : (a) 18.3 Hz, (b) 13.5 Hz, (c) 25.0 Hz, (d) 30.1 Hz, and (e) schematic of a droplet burst flow with $n = 6$ [75, 77].

For the impact of one droplet burst (see **Figure 10**), at $t = 0$ s the local film flow has completely recovered from the impact of the previous droplet burst, but the temperature around the impact area is still lower than the film cooling temperature, showing residual effect from the previous droplet burst. As shown by the changes of T_s and h in **Figure 10** (b) and (c), the cooling enhancement is growing in extent and expanding in area at the early stage of droplet burst impact.

For the impact of one droplet burst flow, the temperature at impact point is measured. Temperature measurement shows that the burst flow causes the temperature to quickly decrease, and then the temperature fluctuates with the constant fluctuation frequency and amplitude in full-developed stage. The fluctuation frequency is equal to the burst impact frequency. The temperature at the impact point remains lower than the film cooling temperature without droplet burst impact. Heat transfer coefficient shows three development stages of the convection: affecting, restoring, and restored. During the restored stage, local cooling has returned to the film cooling. The restored stage may not exist if the time interval between bursts τ , is short (see **Figure 9**). This is because prior to reaching the restored stage the next droplet burst is coming, and local convection heat transfer goes to the next affecting stage.

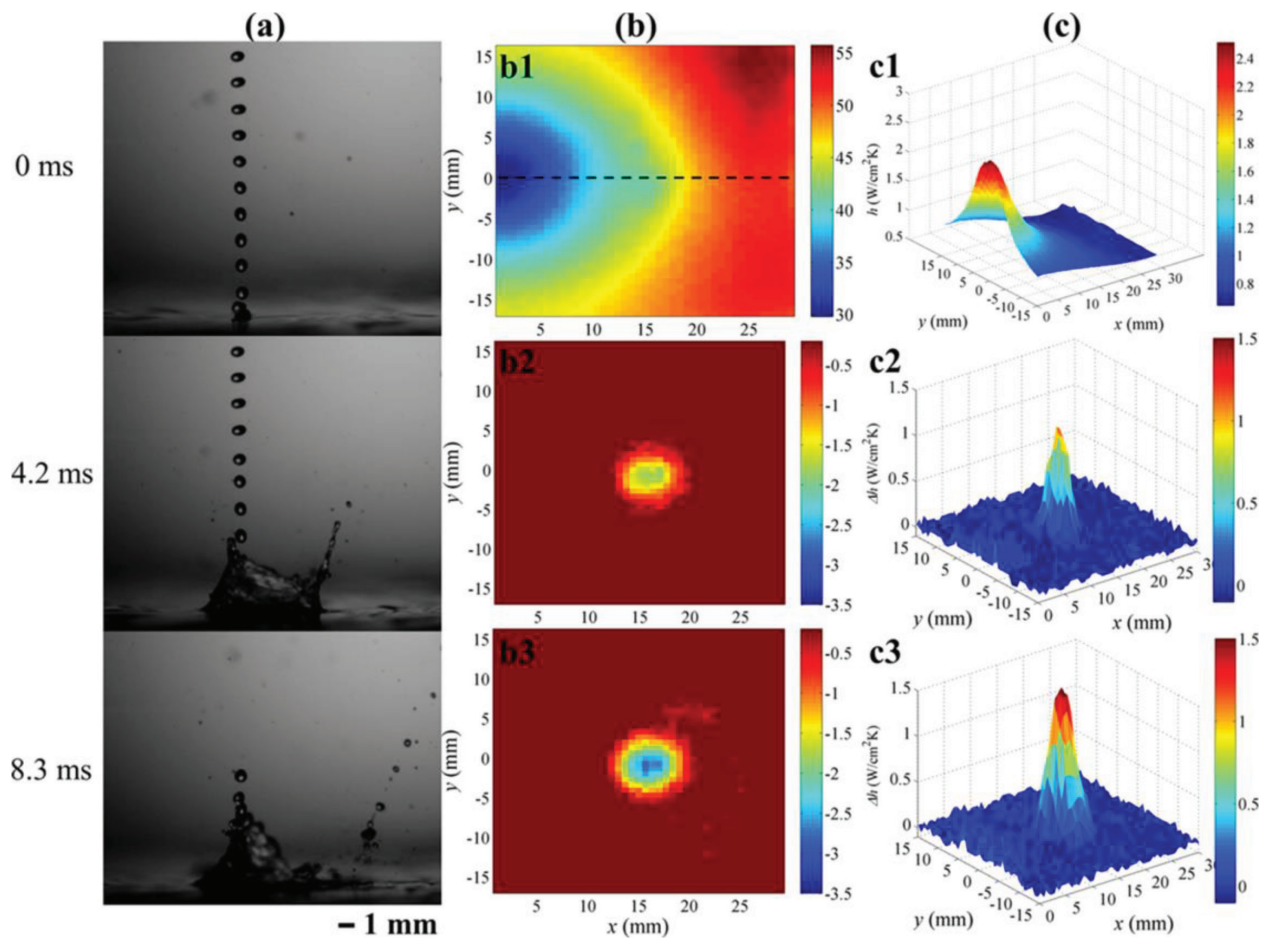


Figure 10. (a) Impact dynamics of a drop burst flow affecting the film flow; (b1) surface temperature distribution at $t = 0$ s; (b2) & (b3) temperature change; (c1) heat transfer coefficient at $t = 0$ s; (c2) & (c3) change of heat transfer coefficient [75, 77].

The comparison of burst flows shows that the trough value of the fluctuating temperature, T_{\min} , decreases with increasing n . The temperature fluctuation amplitude, $T_{\max} - T_{\min}$, is dependent of burst size n and the time interval τ . The mean temperature is related to the number flow rate of the burst flow, indicating the number of droplets landing on the surface per second. The mean temperature decreases with increasing the number flow rate. Increasing the droplet impact velocity leads to the formation of stronger rising liquid sheets during the impact process. Significant increase of impact velocity reduces cooling enhancement due to the local loss of coolant caused by the rising liquid sheets and splashing. These conclusions made based on droplet burst cooling are good for the understanding of droplet characterization influence on cooling performance in spray cooling. The volumetric flux and droplet velocity are coupled in spray impingement. The larger volumetric flux is accompanied by the higher impact velocity. Determining which one is the dominant parameter is not reasonable in spray cooling performance. Observation of droplet burst cooling shows that the larger volumetric flux and proper impact velocity bring the better cooling enhancement.

4. Conclusion

Spray cooling is one effective cooling technology for handling high-power density and high heat flux removal requirement. In spray cooling, liquid coolant is emitted from a pressurized nozzle and breaks up into numerous secondary droplets affecting heated surface that is covered by radially flowing film. The cooling is achieved through the convection heat transfer from the heated surface to the film flow, nucleate boiling, liquid conduction inside the film flow, and interfacial evaporation from the liquid film. Based on research outcomes reported in the literature, spray cooling technology is reviewed from two aspects: the spray level and the droplet level. In the spray level, these studies emphasize the cooling performance to spray property. Some key properties are summarized in this chapter, involving spray characterization, nozzle positioning, phase change, and enhanced surface. In the droplet level, the studies focus on local heat transfer associated with droplet impact conditions, which are classified into a few categories: impact of single droplet on dry surface, stationary film, flowing film, impact of droplet train, and impact of droplet burst. Although spray impact cannot be simply considered as the superposition of single droplets, the studies in droplet level provide experimental and theoretical basis to explain what happened on heated surface and the relevant local heat transfer mechanism in spray cooling.

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