Chapter 7

The Fundamental and Application of Transient Flashing Spray Cooling in Laser Dermatology

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79462

Abstract

Cryogen spray cooling (CSC) has been successfully implemented in laser dermatology such as the treatment of port wine stain. It can protect epidermis from irreversible thermal injuries and increase laser energy, leading to the improvement in therapeutic outcomes. Different from traditional steady spray cooling, CSC is highly transient with short spurt duration (several tens of milliseconds). Besides, CSC can achieve flashing atomization and fine droplets with simple structure nozzles by rapid release of superheat. In this chapter, the mechanism of CSC flashing spray, spray and thermal characteristics of droplets, the measurement method of transient temperature and algorithms for heat flux estimation, and the dynamic surface heat transfer and its relation with spray characteristics are fully discussed. Finally, the heat transfer enhancement of CSC is introduced including alternative cryogens, new nozzles, and hypobaric pressure method to increase the cooling ability, which is essential to improve therapeutic outcome, especially for darkly pigmented human skin.

Keywords: cryogen spray cooling, droplets, dynamic heat transfer, laser dermatology

1. Introduction

When high-pressure liquid is discharged into low-pressure environment below its saturation pressure through a nozzle, the superheated liquid will result in violent flashing boiling spray/flashing spray and two-phase mixture flow [1, 2]. The rapid expansion of vapor bubbles close to the nozzle exit shatters the liquid bulk to produce a finely atomized spray. Different from the hydraulic spray dominated by mechanical breakup, the flashing spray is characterized by explosive atomization, fine droplets, and intense evaporation due to the thermal driving force of unstable superheated liquid returning to its equilibrium state. Low saturation temperature and volatile cryogens, such as R134a, serve as important medium to generate the flashing spray, which has wide applications in many fields due to the fine and uniform droplets with quite low temperature.

As one of the most important applications of flashing spray, cryogen spray cooling (CSC) with R134a has been widely used to protect epidermis from irreversible thermal injuries due to the absorption of laser energy by melanin in the laser treatment of port wine stain (PWS) [3, 4]. PWS is one kind of congenital vascular birthmarks in dermis that occurs in approximately 0.3–0.5% of infants as shown in **Figure 1** [6, 7]. PWS can be associated with significant cosmetic disfigurement and psychological distress. The best choice for the treatment of PWS is laser surgery with selected wavelength to cause permanent thermal damage to the target blood vessels in dermis via the principle of selective photothermolysis [8, 9]. As can be seen from **Figure 2**, however, the competitive absorption of laser energy by melanin in normal tissue (especially in epidermis) will not only reduce the therapeutic effect but also cause irreversible thermal damage to epidermis, due to the close absorption peak of laser energy at the selected wavelength (typically 585 and 595 nm) between the oxyhemoglobin (HbO_2) and melanin. In CSC, a pulsed cryogen spurt with a duration of several decades of milliseconds (no more than 100 ms) is applied to the skin surface prior to laser irradiation in order to selectively cool down the epidermis, aiming to achieve the largest possible temperature difference between epidermis and deeper malformed blood vessels [10–12]. Consequently, CSC enhances the threshold of laser radiant exposure for irreversible thermal damage to epidermis, and higher laser energy can be employed in laser surgery, resulting in the improvement of therapeutic outcomes.

Although CSC-assisted laser therapy has been regarded as the gold standard of PWS treatment, lots of clinical studies have demonstrated that majority of PWS failed to clear completely (less than 20%) [7]. One of the main reasons for the failure of PWS complete clearance is attributed to the insufficient cooling capacity of CSC, especially for the darkly pigmented human skin, which limits the laser energy in clinical surgeries. In general, treatment efficacy correlates negatively with increased melanin content in epidermis due to the strong absorption of laser energy [6]. Therefore, the enhancement of cooling efficiency is quite essential for the further improvement of PWS therapy. Cooling efficiency is usually characterized by

Figure 1. PWS before and after laser treatment (Curtsey of Drs. Wang and Yin at Laser Cosmetic Centre of 2nd hospital of Xi'an Jiaotong University, Xi'an, China) [5].

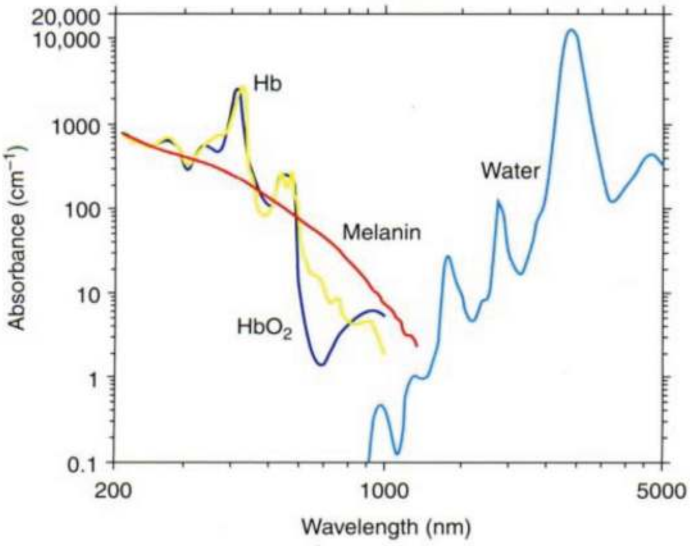

Figure 2. Absorption spectra of major chromophores in skin [9].

dynamic heat transfer, i.e., surface temperature and heat flux on cooling substrate, which greatly depends on spray characteristics including droplet diameter, velocity, and temperature. Therefore, the spray characteristics and heat transfer dynamics of CSC have been studied extensively through experimental method and numerical simulation during the past 20 years.

In this chapter, we will first present a brief introduction of mechanism of flashing spray, and then, we discuss the spray and thermal characteristics of droplets in flashing spray of CSC. Next, we will explain measurement methods of transient surface temperature and algorithms to estimate surface heat flux induced by CSC. The dynamic heat transfer and its qualitative relation with spray characteristics of CSC will also be discussed. Finally, we introduce several heat transfer enhancement methods to increase cooling capacity of CSC including nozzle design, alternative cryogens, and hypobaric pressure method.

2. Flashing spray mechanisms

Usually, flashing spray can be obtained by isothermal pressure drop (line OA in **Figure 3**), during which the liquid from its initial stable sub-cooled condition (O) quickly goes into a metastable superheated state (A). The faster the process, the more violent flashing spray can be reached. The spinodal line close to the liquid saturation line represents the thermodynamic limit of metastable liquid region, which can be evaluated by $(\partial P/\partial v)_T = 0$. The extent of metastable liquid is usually represented by superheat degree in terms of $\Delta T = T1 - T_{sat,\,PA}$ or $\Delta P = P_{sat,T1} - P_A$. The superheated liquid always has the nature of returning to its equilibrium state through rapid phase transition, which starts from vapor bubble nucleation through bubble growth to the eventual stable liquid-vapor equilibrium. There are two types of nucleation processes identified as homogeneous and heterogeneous nucleation. The former

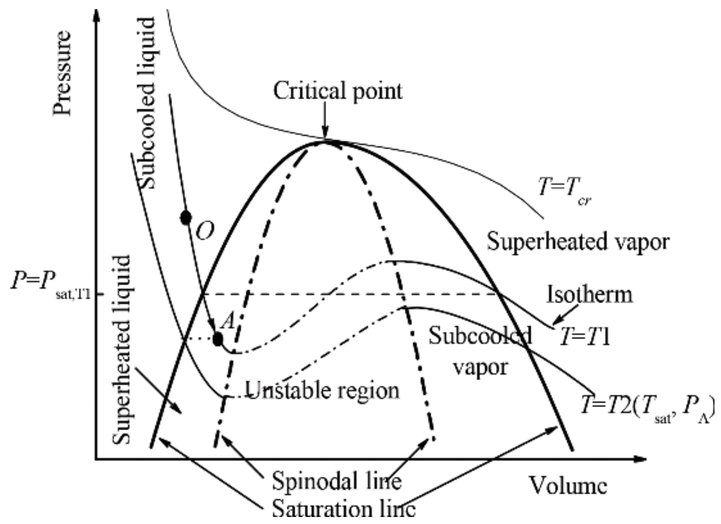

Figure 3. Schematic of pressure-volume isotherm for a pure fluid [13].

is a fundamental mechanism of first-order phase transitions, occurring in the volume of the superheated pure liquid, whereas the latter initiates from the boundaries of the liquid phase with either impurities (including dissolved gas micro-bubbles and dust) or container walls and is a second-order phase transition. Once the nuclei are larger than a critical value, they will grow further to generate bubbles.

According to the location of phase transition happening, there are two models of flashing spray [14]. One is the external flashing, and phase change only occurs outside the nozzle, which is

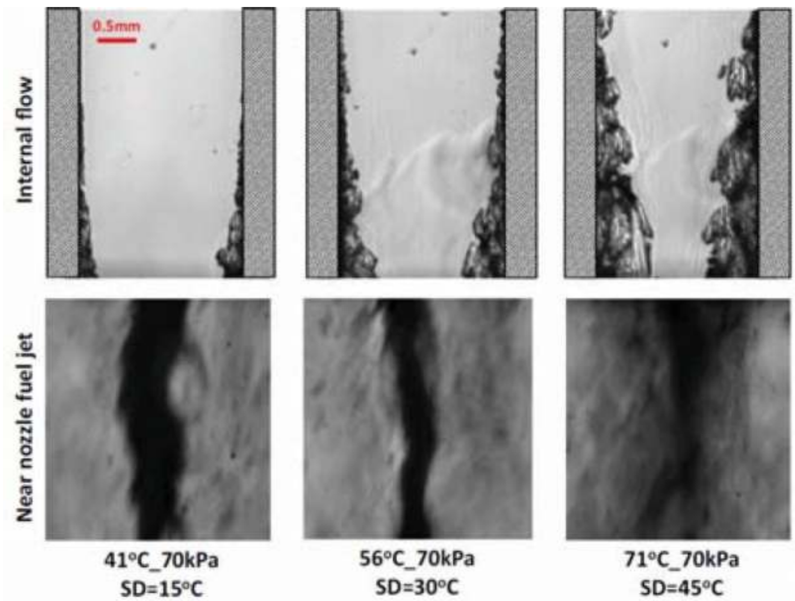

Figure 4. Effect of fuel temperature on internal flow and near nozzle n-pentane fuel spray characteristics [17].

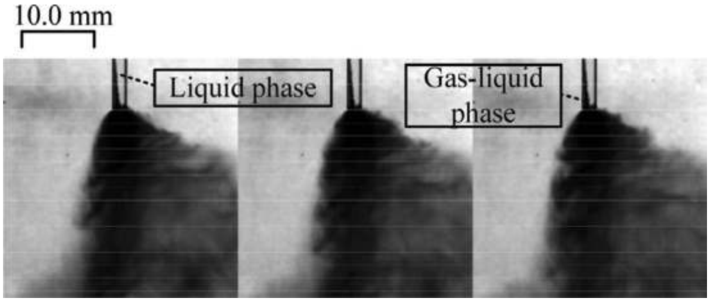

Figure 5. Internal flow and spray pattern near nozzle field of R134a flashing spray [18].

usually difficult to achieve. The other is the internal flashing and more commonly occurs in various applications in which phase change takes place either within the internal nozzle or simultaneously inside and outside the nozzle. In this model, different spray pattern of two-phase flow before discharge can be obtained from the initial bubbly flow to slug flow and annular flow with increasing the superheat degree [14–16]. It is noticed that the internal flow governs the atomization behavior outside the nozzle. For such case, more violent atomization and larger spray angle occur with higher superheat degree, i.e., higher void fraction. Usually, high superheat and long nozzle with small diameter are more likely to generate internal flashing spray, while low superheat and short nozzle with large diameter have more possibilities of inducing external flashing spray. Most previous studies about internal flashing spray using water and hydrocarbon mediums indicate that bubble formation inside nozzle is in favor of atomization with larger spray angle as shown in **Figure 4** [17]. However, recent study of R134a flashing spray shows the opposite trend that phase change/bubble formation inside nozzle mitigates the intensity of flashing atomization outsize the nozzle with smaller spray angle shown in **Figure 5** [18]. This is explained by the fact that the prior phase change inside the nozzle greatly decreases liquid/vapor temperature, corresponding to a lower superheat degree as they are discharged.

3. Spray and thermal characteristics of flashing spray

The release of superheat of flashing spray is quite rapid and only occurs near nozzle field, resulting in the breakup of liquid into fine droplets. Then droplets experience equilibrium evaporation as well as heat and momentum interaction with ambient gases. As a result, their diameter, velocity, and temperature continuously vary within the flow field. These spray and thermal characteristics have an important effect on heat transfer performance on cooling substrate. Currently, R134a is the only cryogen that gets the allowance of application in laser surgery by US Food and Drug Administration (FDA). Therefore, most attentions have been paid on R134a spray and thermal characteristics, and stainless steel straight tube nozzle is usually employed with length ranging in 20–80 mm and diameter ranging in 0.3–1.5 mm. Droplet diameter and velocity can be simultaneously measured by Phase Doppler Particle Analyzer (PDPA) based on the principle of light interface, or droplet diameter can be also measured by Malvern based on Mie scattering theory. Both of the measurement methods are noninvasive, having no disturbance to spray field.

Pikkula et al. [19, 20] investigated the effect of droplet velocity and diameter on heat removal during R134a flashing spray, employing four different types of nozzles including full and hollow cone spray nozzles and straight tube nozzle. They found that nozzle type greatly influences droplet diameter and mass flow rate while has less effect on heat removal on cooling substrate. They also found a nonlinear relationship between heat removal and Weber number, and a higher Weber number was in favor of cooling capacity. Karapetian et al. [21] explored mass flow rate and droplet velocity on surface heat flux of R134a flashing spray using eight straight-tube nozzles with four different diameters (0.57, 0.83, 1.08, and 1.33 mm) and two different lengths (8 and 65 mm). Their results showed that change in mass flow rate on heat flux was more important than that of droplet velocity. For fully atomized sprays, however, larger droplet velocity could substantially enhance surface heat flux. Aguilar et al. [10, 22, 23] also investigated the effect of nozzle diameter and length on spray characteristics of R134a flashing spray. In contrast to nozzle length, nozzle diameter had greater influence on the spray characteristics. Larger diameter nozzle with shorter length generated jet-like spray with higher droplet velocity and larger droplet diameter, while smaller diameter nozzle caused more finely atomized spray with lower droplet velocity and smaller droplet diameter. Vu et al. [24] further investigated the effect of nozzle length (20, 40 and 80 mm, with same inner diameter of 0.5 mm) on spray behavior of R134a flashing spray, but no obvious difference of external spray characteristics was observed. They also proposed a simple two-phase flow model inside straight-tube nozzle to explain the acceleration of droplet velocity near nozzle field that the higher velocity airflow accelerated the lower velocity droplet. Zhou et al. [25] obtained droplet density, diameter, and velocity evolution along both radial and axial directions within flow field. A sharp decrease in droplet diameter and an increase in droplet velocity near nozzle field were found, while their variation became more gradual in the far field of spray. They proposed nondimensional correlation of droplet density and velocity distributions based on the experimental data. Zhou et al. [26] also investigated the effect of different cryogens R134a, R407C, and R404A on spray characteristics. Their study indicated that more volatile cryogen induces better atomization, generating higher droplet velocity and smaller size diameter. Yildiz et al. [27–29] studied spray characteristics of R134a flashing spray with larger inner nozzle diameter (1–5 mm) and subcooled cryogen liquid pressurized in a high-pressure container. Much different with the atomization phenomenon of previous studies by Pikkula, Aguilar, Vu and Zhou, they observed that flashing only occurred outside nozzle exit that liquid column suddenly shattered at certain distance from nozzle tip, while flashing already happened inside nozzle for other studies. This kind of external flashing spray generated far larger droplet diameter than those by internal flashing spray.

Compared to the investigation on droplet diameter and velocity, there were only few studied on droplet temperature. A big challenge is the difficulty of measuring low droplet temperature in volatile flashing spray through noninvasive methods. Alternatively, the intrusive method with a fine thermocouple is usually employed to obtain droplet temperature quantitatively, while disturbance cannot be avoided to spray. Aguilar et al. [10] and Yildiz et al. [30, 31] investigated droplet temperature evolution along central spray axis with the intrusive thermocouple. Droplet temperature first experiences a fast exponential decay

http://dx.doi.org/10.5772/intechopen.79462

near nozzle field and then decreases more slowly with spray axial distance until reaching the minimum temperature. Although nozzle diameter affects the decreasing rate of droplet temperature, the minimum temperature of R134a flashing spray is independent of nozzle diameter, always equaling to −60°C. The distance of the minimum temperature occurring was defined "minimum temperature distance" by Polanco et al. [32]. They also reported a dimensionless minimum temperature distance ranging from 150 to 170 (normalized by nozzle diameter) for R134a and propane flashing spray. Later, Zhou et al. [25] conducted a much more comprehensive study on the global thermal characteristics of R134a flashing spray with an inserted thermocouple of 0.1 mm. It was found that a warm core existed near nozzle field where droplet radial distribution showed "W" shape, while it transited to a "U" shape in the far field of spray as shown in **Figure 6**. They also proposed two thermal widths (thermal width R_{STW} and cold width R_{SCW}) and a correlation to describe droplet temperature variation along axial distance.

In addition to the experimental studies, numerical simulation provides alternative way to study flashing spray. However, most of numerical studies concern the fuel flashing spray in internal combustion engines. Few numerical studies pay attention to cryogen flashing spray with very low saturation temperature and high volatility. Recently, Zhou et al. [33] explored the spray morphology, droplet diameter, velocity and temperature behavior of R404A flashing spray through OpenFOAM, and their result matched experimental data reasonably although some discrepancy existed in the near nozzle field. Wang et al. [34] conducted numerical study on R134a flashing spray near the nozzle exit by a three-dimensional vortex method and explored the effect of spray back pressure, ambient temperature, and mass flux on the heat flux on cooling surface. Their results could predict spray distance and back pressure for specific heat flux peak at any ambient temperature and nozzle diameter, which provided personalized and precise reference for parameter selection in clinical spray cooling.

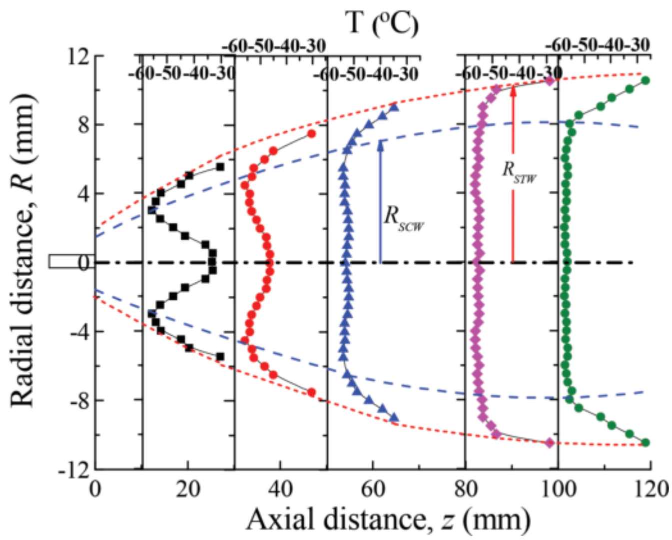

Figure 6. Radial temperature distribution of R134a flashing spray at various axial distance [25].

4. Dynamic surface heat transfer of CSC

4.1. Transient surface temperature measurement and heat flux calculation

During the short pulse spray less than 100 ms, surface temperature and heat flux undergo extremely rapid variations as droplets impinge on cooling substrate. Thus, surface temperature measurement and heat flux calculation are challenges and are also important for CSC. Additionally, it is quite difficult to carry on experiments with real human skin. Usually, researches use epoxy resin and plexiglass as skin phantoms in experiments due to their similar thermal physical properties with skin tissue. There are two methods to measure the transient surface temperature as shown in **Figure 7**. One is the indirect method that commercial thermocouples of round or plate-shaped joints with at least 50 μm coverer by a thin layer of aluminum foil are placed on the cooling substrate surface. As a result, the thermocouple is not directly exposed to the droplets of the spray, which usually gives a poor response of the surface temperature in the order of a few milliseconds [36]. The other one is using thin film thermocouple (TFTC) with thickness of ~2 μm to measure the surface temperature directly, since TFTC is deposited onto the cooling substrate surface through Magnetron technique. It has perfect contact with the underlying substrate and a fast response time (1 μs) [4]. Therefore, the surface temperature measured by TFTC varies much faster than by indirect method as shown in **Figure 8**.

It is far more difficult to measure the time-varying heat flux directly at the solid surface than to measure surface temperature. Alternatively, it is usually estimated from the temperature measurement made at accessible locations, which is termed an inverse heat conduction problem (IHCP). Several analytical and numerical methods have been proposed for the solution of IHCP, such as specified sequential function method (SFSM), regularization method, and transfer function method, among which the most popular method for estimation of surface heat flux is SFSM. Tunnell et al. [19, 37–39] predicted surface heat flux during and following cryogen spurt using the SFS method based on internal temperature measurement, in which a wire-like thermocouple with a bead diameter of 30 μm was imbedded in epoxy resin. Aguilar et al. [36, 40, 41] also employed the SFS method to estimate surface heat flux during CSC

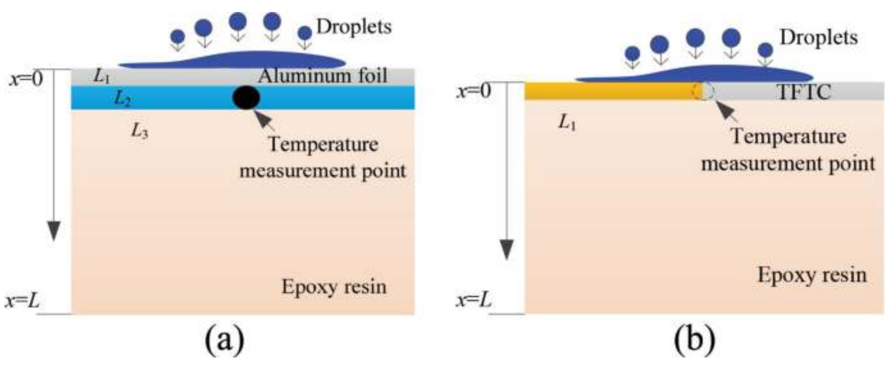

Figure 7. Schematic of the two different surface temperature strategies [35]. (a) Indirect measurement of surface temperature by covered thermocouple; (b) Direct measurement of surface temperature by TFTC.

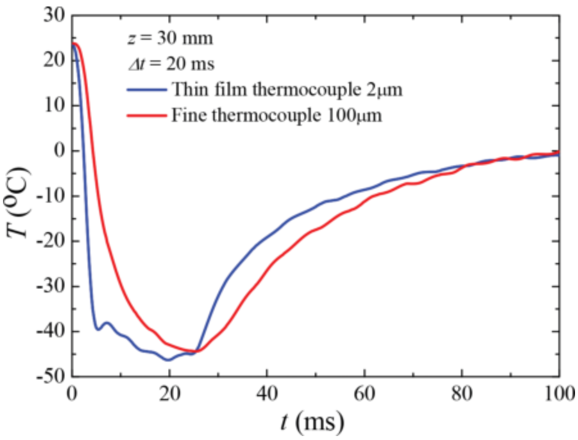

Figure 8. Comparison of transient surface temperature measured by indirect and direct methods [35].

based on internal temperature data measured by indirect measurement method. Using the same temperature measurement method, Franco et al. [42, 43] calculated the surface heat flux by solving a direct problem through Duhamel's theorem, where the measured temperature was treated as the real surface temperature. Zhou et al. [4, 44, 45] also predicted surface heat flux with Duhamel's theorem but based on surface temperature measured directly by TFTC. It should be noticed that the Duhamel's theorem is only applicable to the calculation of surface heat flux at the condition of surface temperature measured directly. Otherwise, it causes much error to the heat flux result. Later, Zhou et al. [35] developed a new method based on Duhamel's theorem that could predict surface heat flux accurately in both cases of indirect and direct surface temperature measurement methods. However, all the previous studies about CSC, heat transfer within the cooling substrate during CSC was treated as one dimensional heat conduction problem, only taking into account heat transfer along the depth direction while ignoring the latent heat transfer. Recently, [46] proposed a two dimensional model to predict surface heat flux through a filter solution method. Their result indicated that the maximum heat flux was 13.6% higher than that predicted by 1D heat conduction model.

4.2. Parametric study on heat transfer of CSC

Great efforts have been made to investigate the heat transfer characteristics of R134a spray cooling under various conditions during the past two decades. Aguilar et al. [36, 47] extensively studied the effect of spurt duration and spray distance. Their results showed that the surface temperature and heat flux were significantly affected by the spray distance while little influenced by the spurt duration. They also studied the effect of the spray angle between the nozzle and the cooling surface [41]. The result indicated that there was insignificant effect on heat flux and heat extraction at a wide range of spray angles (15 ~ 90°). Jia et al. [40] investigated the initial temperature of the cooling substrate. It was found that a higher initial temperature could cause a greater heat flux. Franco et al. [43] and Wang et al. [44] investigated the radial variation of heat transfer during CSC and found a sub-region of uniform cooling at the center of the sprayed surface. Pikkula et al. [19] explored heat removal during CSC using different nozzles and found no apparent variation, despite the relatively large difference in cryogen mass output. Majaron et al. [48] observed water condensation and frost formation on cooling substrate during CSC. It was found that the latent heat deposited by condensation of water vapor and subsequent frost formation significantly impair CSC cooling rate while may reduce the risk of cryo-injury associated with prolonger cooling. Ramirez-San-Juan et al. [49] investigated the effect of ambient humidity on light transmittance during CSC due to scattering of light by the spray droplets and subsequent water condensation/freezing on skin surface. They found that light transmittance was greatly reduced with increasing humidity caused by more intense condensation of water vapor at higher ambient humidity. Vu et al. [50] used a wire meshes in the spray path to enhance cryogen spray atomization in order to enhance cooling efficiency on cooling substrate. However, this passive way did not succeed in enhancing cooling efficiency, while it could prolong cooling duration for larger nozzle. Majaron et al. [51] employed a split injection strategy (intermittent spray) to eliminate liquid film formation on cooling substrate of metal disk, which impaired heat transfer due to relatively low thermal conductivity, and found that highest cooling rates reached at moderate duty cycle levels. Basingerd et al. [52] found that skin indentation due to the force of an impinging cryogen spray reduced heat transfer efficiency of CSC because of cryogen accumulation compared to the flat surfaces. But once indentation existed, larger indentations produced a higher maximum heat flux caused by the stronger convective flow within the cryogen pool.

Heat transfer coefficient served as a boundary condition is quite crucial for calculation of temperature distribution within cooling substrate or skin during CSC. However, previous studies did not yield a general correlation of heat transfer coefficient of CSC. Recently, Tian et al. [53] found that transient cooling could be divided into two stages, namely, fast boiling cooling and film evaporation cooling. The similarity of dynamic heat flux with different cryogens, nozzles, and substrates was observed, and a dimensionless correlation was proposed, as presented in **Figure 9**. As to the maximum heat flux, a nondimensional correlation was proposed by coupling the Jakob number (Ja), Reynolds number (Re_l), and Weber Number (We), as shown in **Figure 10**.

Although CSC selectively cools and protects epidermis from thermal injuries in dermatologic laser surgery, aggressive cooling may have the risk of causing cryo-injuries to epidermis and dermis. Kao et al. [54, 55] studied the potential for epidermal and dermal injury exposed to continuous CSC spurt durations of 10, 20, 40, 80, 100, 200, and 500 milliseconds through experimental study using a vitro model of human skin (RAFT). It was found that spurt duration longer than 100 ms could result in epidermal injury acutely, and 500 ms spurt duration of CSC even could cause decreased fibroblast proliferation to dermis. Li et al. [56, 57] also simulated the cooling process and evaluated the potential cold injury of CSC with R134a, R407C, and R404A through a multiscale model, in which cold injury was recognized once cells were dehydrated or the ice formed intracellularly. They reported spurt duration causing cold injury were 3.3, 2.2, and 1.9 s for R134a, R407C, and R404A, respectively, which was much longer than that reported by Kao et al. [54, 55]. For actual clinical application of CSC, the spurt duration is controlled within 100 ms, which should not cause cold injury to both epidermis and dermis.

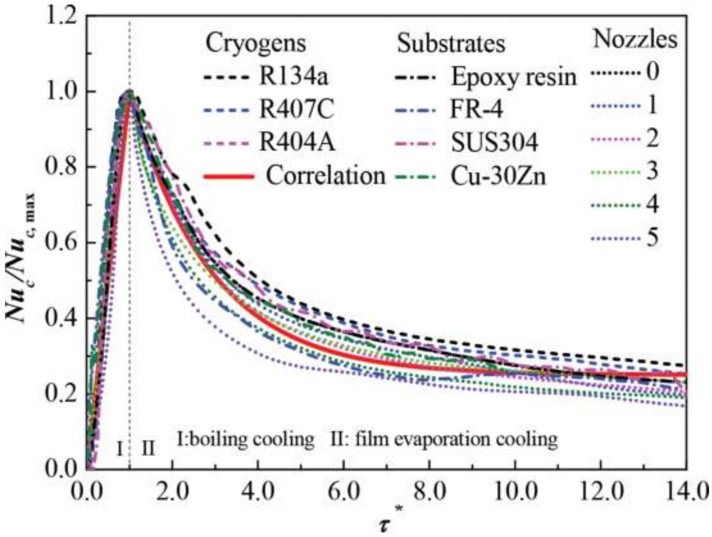

Figure 9. Similarity of nondimensional heat flux at various conditions, different cryogens, cooling substrates and nozzles.

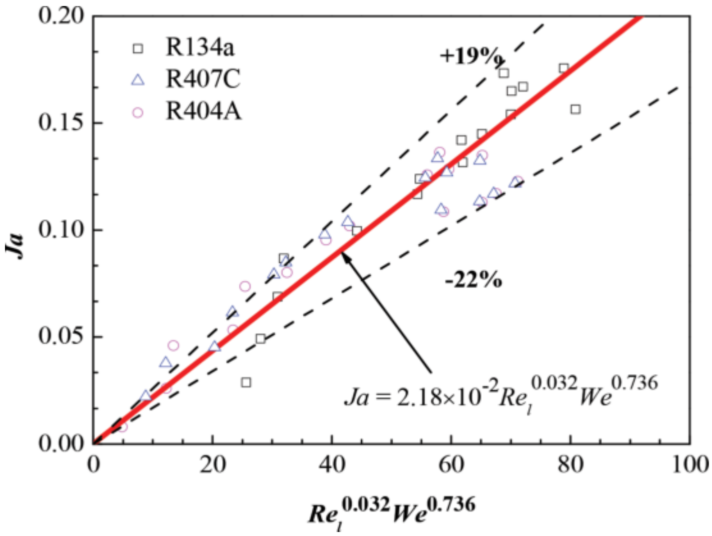

Figure 10. Dimensionless correlation of maximum heat flux [53].

5. Heat transfer enhancement of CSC

CSC is of much importance during dermatologic laser surgery, reducing thermal injury to epidermis, and increasing laser energy for treatment of PWS. However, the therapeutic outcome is still not satisfied (the complete clearance of PWS is less than 20%), and thermal injury of epidermis commonly occurs especially for dark human skin like Asians, which greatly limits the allowance of laser energy in clinical surgery [7]. One of the most important reasons lies in the insufficient cooling efficiency induced by CSC. Thus, several strategies have been proposed to further improve the cooling efficiency in past 20 years.

New cryogens with a lower saturation temperature and higher volatility are essential for enhancing the cooling capacity of CSC based on the current spray technique. Alternatively, cryogens R407C and R404A meet the requirement, with a far lower saturation temperature of −43.6 and −46.5°C at 1 atm, respectively. Moreover, they share a similar feature with R134a in that they are nontoxic to the human body and friendly toward ozone depletion. Dai et al. [58] first carried out preliminary studies on the heat transfer of R404A spray cooling for the laser dermatology of PWS. They used a 30-μm diameter thermocouple, embedded at a 100-μm depth below the phantom surface, to measure the temperature at a long spray distance (85 mm). Their work revealed that R404A spray cooling produced a lower surface temperature than that of R134a and did not cause any cold injuries to skin within 300-ms spray duration. Zhou et al. [45] investigated the effect of spray distance and spurt duration on heat transfer characteristics during CSC with R404A through a thin film thermocouple of 2-μm thickness. It was found that the minimum surface temperature appeared at a spray distance of 30 mm, and a slightly higher heat flux could be obtained for a shorter spray distance, whereas the spurt duration had little effect. Later, Zhou et al. [26] did a comparative study on the spray behavior and heat transfer dynamics using different volatile cryogens (R134a, R407C, and R404A), further demonstrating the priority of R404A spray cooling with lowest surface temperature and highest heat flux with regard to the cooling capacity. The maximum heat flux was 20% higher by R404A than that by R134a, while the liquid film resistance time was 50% less than that by R134a spray cooling. In addition, quite different from the divergent morphology of R134a spray, R404A presents a convergent spray pattern toward axial distance with much smaller spray width after its rapid expansion at nozzle exit as shown in **Figure 11** because of its higher volatility, which is helpful to the precise control of cooling region in clinical surgery [59]. All the above studies indicate that R404A has much potential of substituting the current R134a in the application of laser dermatology, especially in the case of darkly pigmented human skin. However, all R134a, R407C, and R404A have a high global warming potential (GWP > 1000) which limits their use in future according to the Kigali

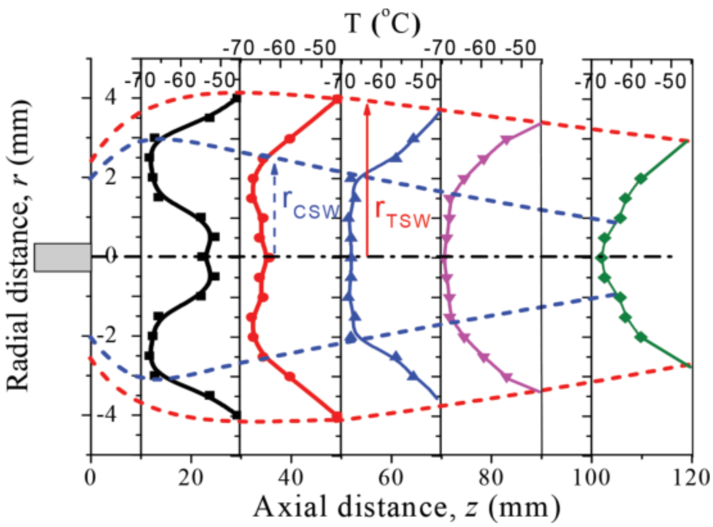

Figure 11. Radial temperature distribution of R404a flashing spray at various axial distance [59].

agreement signed in 2016. Wang et al. [60] firstly suggested using R1234yf as a substitute of traditional HFCs in CSC application due to its extremely low GWP of 4 and its similarity of thermal property with R134a. Their experimental results indicated that the cooling capacity of R1234yf spray was a bit lower than that by R134a, but its cooling efficiency could be enhanced through reducing the superheat degree of flashing spray.

Aguilar et al. [61, 62] proposed a hypobaric pressure-modulatable technique, in which a close chamber and a vacuum pump were used to lower the spray back pressure, by which the surface temperature was reduced and the heat extraction from the cooling substrate was enhanced. Moreover, low pressure could induce vasodilation, which facilitated the easier absorption of laser energy by small blood vessels [63]. This technique was recommended as a promising mechanical way of offering better protection for the epidermis and further improving the therapeutic outcome of PWS [6]. Recently, Zhou et al. [4, 64] employed this technique to investigate the coupling effect of spray distance and back pressure on surface temperature and heat flux during CSC with R134a and R404A. The results proved that the droplet diameter and velocity were greatly reduced due to the enhanced evaporation rate through lowering the back pressure. Heat transfer presented different varying trend with spray back pressure at different spray distances. For R134a spray cooling, the maximum heat flux could be enhanced from 247 to 641 kW/m^2, when the back pressure was lowered from atmospheric pressure to 0.1 kPa at very short distance of 10 mm as shown in **Figure 12**. However, aggressively lowering back pressure below the transitional pressure could lead to a reduction of maximum heat flux at other longer spray distances. Therefore, the spray distance and back pressure should be appropriately deployed to ensure a high heat flux. It is recommended to use the shorter spray distance (10 ~ 20 mm), when the pressure is no larger than the transitional pressure, whereas to use the longer spray distance (40 mm), when the pressure is around 50 kPa. For the atmospheric pressure, 30 mm is the most suitable spray distance.

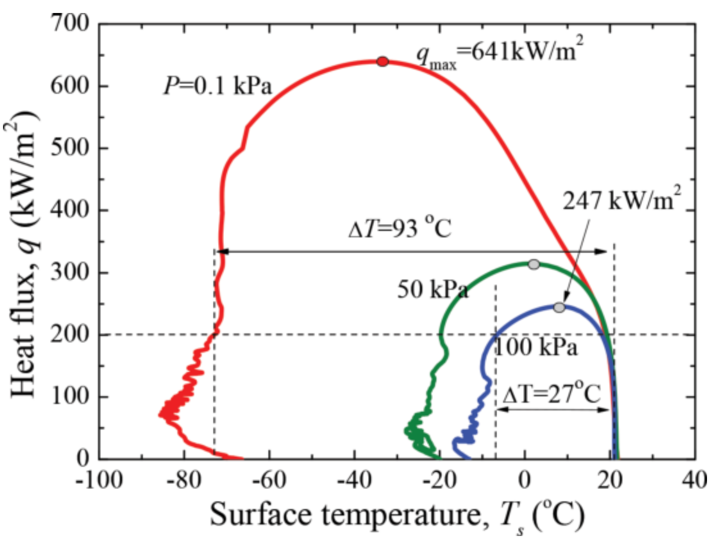

Figure 12. Variation of surface heat flux with surface temperature under different spray back pressures at the distance of 10 mm [4].

Wang et al. [44, 65] designed a cylindrical expansion chamber nozzle with different aspect ratios of chamber length to width for CSC application. Cryogen liquid experienced a first flashing atomization to release part of superheat inside the expansion chamber before discharge from the subsequent straight-tube nozzle. Therefore, this kind of nozzle resulted in much lower droplet temperature and narrower spray width near nozzle field, which enhanced the maximum heat flux by 60% compared to the traditionally used straight-tube nozzle at the optimized aspect ratio of ~0.5.

6. Conclusions

With the rapid development of laser dermatology, protection of normal skin tissue becomes increasingly important for improvement of therapeutic outcomes and attracts more and more attentions in order to optimize the cooling efficiency. This chapter presents a brief review of the progress of cryogen spray cooling in laser surgery for the treatment of port wine stain, focusing on flashing spray mechanism, spray and thermal characteristics of droplets, dynamic heat transfer, and strategies of heat transfer enhancement. Using simple structure nozzle can achieve good atomization characterized by fine droplets with diameter from 5 to 20 μm and velocity usually below 60 m/s induced by internal flashing and release of remaining superheat of liquid at nozzle exit. The explosive atomization near nozzle field also leads to low droplet temperature below its saturation temperature, and the continuous evaporation in flight further reduces droplet temperature. The impingement of droplets results in a strong dynamic heat transfer involved heat conduction, impinging convection, nucleate boiling, and surface evaporation on cooling surface during the transient flashing spray, which rapidly lowers surface temperature and removes heat from epidermis while almost has no effect on the temperature of underlying layer of dermis. Several new methods of using expansion chamber nozzle, substitute cryogens and hypobaric pressure method have been proposed to enhance its cooling efficiency.

Although great progresses have been achieved in both clinic practice and physical understanding of cryogen spray cooling in the past two decades, many issues still remain. First, the fundamental and governing principal of internal flow inside the mini-nozzle on the external flashing spray is not clear enough and needs further exploration. Second, noninvasive measurement of droplet information for dense spray near nozzle field is still a big challenge especially for low temperature measurement of two phase flow. Third, although heat transfer performance greatly depends on spray and thermal characteristics, the fundamental of their relationship is quite complicated and affected by various factors in this transient flashing spray. It is important to develop a theoretical model to connect these two physical processes and thus can have a better guidance of cooling optimization. Last but not the least, although several strategies of heat transfer enhancements have been recommended from the mechanical perspective, much effort of clinical study is needed to demonstrate the feasibility and priority of these new methods in clinical practices.

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