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Research Paper

Parametric effect investigation on surface heat transfer performances during cryogen spray cooling

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HIGHLIGHTS

- Effects of ambient temperature and humidity on surface flux were investigated.
- Best cooling capability can be obtained when ambient temperature (T_a) is 10 °C.
- High T_a causes the decrease in droplet amount and increase in droplet temperature.
- Frost formation under high relative humidity weakens cooling capability of CSC.
- 2D surface heat flux was obtained by filter solution method.

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ABSTRACT

Cryogen spray cooling (CSC) has been a widely used auxiliary tool in laser dermatology such as port wine stain to prevent unspecific thermal injury due to laser energy absorption by the melanin in the epidermis. The present paper presents an experimental research on the effect of ambient temperature, relative humidity, and initial substrate temperature on heat transfer performances during R134a spray cooling. Results demonstrated that the cooling capability of R134a spray cooling can be obtained with small ambient temperature (T_a = 10 °C) and relative humidity (RH = 25%). Further investigation of cooling mechanism was conducted by studying the temporal and radial heat transfer distributions with different spray distances and nozzles. The heat transfer distribution presented large non-uniformity along radial locations. Two uniform cooling sub-regions of $0 \le r < 2$ mm and 6 mm $\le r < 10$ mm were found under the spray distance of 30 mm and nozzle with an inner diameter of 1.0 mm. The heat transfer barrier was produced due to indirect contact between cold droplets and the substrate surface caused by bubbles and heat transfer is weakened by the low thermal conductivity of these bubbles.

1. Introduction

Port wine stain (PWS) birthmarks are congenital and progressive vascular malformations of the capillaries in the dermis and are found in approximately 0.3%–0.5% of children. Recently, a pulsed dye laser (PDL) with a wavelength of 595 nm or 585 nm has effectively treated PWS based on the principle of selective photothermolysis [1,2]. The energy density of pulsed dye laser (PDL) with a wavelength of 585/595 nm and1.5 ms pulse width is in the range of 3–10 J/cm^2 [3,4]. However, a significant amount of laser energy is absorbed by the melanin in the epidermis before the laser approaches the blood vessels buried in the dermis, thereby yielding thermal damage and successive skin dyspigmentation or hypertrophic scarring [1]. In 1995, Nelson et al. [5,6] introduced cryogen spray cooling (CSC), which has been an important assistant cooling tool used in the treatment of vascular skin lesions such as PWS. Prior to laser irradiation, a CSC with a spurt duration smaller than 100 ms can minimize the risk of epidermis heat injury induced by laser and increase incident laser energy, thereby improving laser treatment efficiency [7,8]. Although CSC has been widely used in PWS laser treatment, the complete cure rate for darkly pigmented human skin is still less than 20% due to the nonspecific thermal injuries induced by insufficient cooling [9,10]. Such insufficient cooling can be attributed to the lack of understanding of surface heat transfer mechanism.

In addition to the application in the treatment of PWS, CSC is also widely applied with increasing interest for electronic cooling and other high heat flux removal applications [11–14]. Unlike traditional spray cooling, CSC combines strong atomization, droplet evaporation, and

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Nomenclature

c	specific heat capacity (kJ/kg·K)
D	inner diameter of nozzle (mm)
f	filter coefficient
$\mathbf{F}$	filter coefficient matrix
$\mathbf{H}_t$, $\mathbf{H}_s$	temporal and spatial first order regularization matrix
J	number of sensors
L	length of nozzle (mm)
m	column index
m_f, m_p	number of future and past time steps
n	time step index
q	surface heat flux (kW/m^2)
$\mathbf{q}$	surface heat flux matrix
r	radial location (mm)
r_s	liquid film radius (mm)
RH	relative humidity (%)
S	sum of squares of the temperature errors
t	time (ms)
T	surface temperature (°C)
$\mathbf{T}$	real temperature matrix
$\mathbf{X}$	sensitivity matrix
$\mathbf{Y}$	measured temperature matrix
Z	spray distance (mm)

Greek symbols

α_t, α_s	temporal and spatial regularization parameter
λ	heat conductivity coefficient (kW/m·K)
ρ	density (kg/m^3)
Δt	spray duration (ms)
Δx	interval between every two thermocouples (mm)
τ	liquid film residence time (ms)

Subscripts

a	ambient value
d	droplet
k	surface heat flux index
0	initial value
min	minimum value
max	maximum value

surface boiling, thereby making it a complex transient phase-change heat transfer process. Researchers have conducted numerous experimental investigations. Interests focused on the heat transfer performances on skin phantoms, including the effects of spray distance [15], spurt duration [16], spray angle [17], cooling medium [7], nozzles [8], hypobaric pressure [18], initial temperature [19], and relative humidity [20], etc. The results indicated that short spray distance and high initial temperature significantly increased surface heat flux. However, spray duration and angle had a slight effect on surface heat flux. Zhou et al. [7] carried out comparative investigations in terms of the surface heat transfer and spray dynamics among R134a, R407C, and R404A. They found that R404A can enhance heat transfer mainly due to low boiling temperature (−46.5 °C at 1 atm). A new nozzle with an expansion chamber was also introduced by Zhou et al. [8] to increase the maximum surface heat flux by 18% with a length-to-diameter ratio (L:D) of 1:1. Compared with straight stainless nozzle, the decrease in the secondary atomization and temperature in the expansion chamber enhanced heat transfer. Moreover, Zhou et al. [18] investigated the coupling effect of hypobaric pressure and spray distance on the heat transfer performances of R134a. They found that reducing spray back pressure always enhanced cooling capacity, and the maximum surface heat flux with 0.1 kPa was 2.6 times as that with 101 kPa. Majaron et al. [21] and Franco et al. [20] investigated the effect of relative humidity on heat transfer performances during R134a spray cooling. Their results implied that high relative humidity impairs the cooling rate, and the frost formation following CSC may cause the attenuation of incident laser light. It should be emphasized that the evaporation of droplet and liquid layer during CSC largely depends on ambient conditions (ambient temperature and humidity), which considerably influence cooling performance. However, a comprehensive investigation of ambient temperature effect has yet to be conducted. Although numerous works have been conducted on the heat transfer performances of CSC, systematic and in-depth investigations of the preceding effects mentioned are still rare. Moreover, additional efforts should be devoted to better understand the surface heat transfer mechanism, which is important to enhance the spray cooling capability. Moreover, the previous investigations [22,23] have demonstrated that the nozzle diameter and spray distance have significant effects on the cooling performance. However, it is not established the coupling effect of nozzle diameter and spray distance on the cooling performance.

In the most of the preceding results mentioned above [15–17,19–21], temperatures were all obtained by a fine type-T thermocouple (FTC). In FTC measurement [24,25], a type-T thermocouple (50 µm bead diameter) was placed underneath a thin layer of aluminum foil (20 µm). The foil was positioned on top of the epoxy resin to provide rapid heat transfer from cooling cryogen droplets and mechanical support. However, capturing the rapid change of surface temperature for FTC measurement is difficult due to the heat transfer delay induced by the thin aluminum foil. Thus, a large measurement lag occurred in temperature change. Also, the surface heat flux was estimated by 1D Duhamel method based on measured temperature. Based on the assumption of uniform lateral temperature distribution, 1D Duhamel method could result in large inaccuracy in surface heat flux [26] due to neglect of lateral heat transfer. Nevertheless, a large non-uniformity of heat transfer has been found in our previous work [8]. A sub-region of uniform cooling with a radius of 2 mm around the spray center exists under the optimal spray distance of 30 mm. In the sub-region of 2 mm ≤ r < 10 mm, the minimum surface temperature increases and maximum surface heat flux decreases with increasing the radial distance. Since a large non-uniformity of heat transfer exists in the cooling area, the investigation of heat transfer performance just on spray center cannot represent the whole cooling performance distribution in the entire cooling area.

Compared with FTC measurement, thin-film type-T thermocouple (TFTC) had the advantages of small heat capacity, fast response, and accurate measurement. Furthermore, temperatures at different radial locations can be measured by one test, thus increasing experiment efficiency. Also, the measurement of temperature at different radial locations can comprehensively evaluate cooling performance under different working conditions. In our previous work [8], the non-uniformity of temporal and radial heat transfer with a TFTC measurement was investigated during R404A spray cooling. A sub-region of uniform cooling with a radius of 2 mm around the spray center was found. Temperatures at different radial locations were measured by repeated operations of relative location removal between the nozzle and the substrate, thus resulting in the inefficiency of the experiment. However, heat flux was still computed using 1D Duhamel method.

In our previous work, we have developed a two-dimensional filter solution for 2D single and multi-layer geometries to estimate the surface heat flux [26]. Compared with 1D Duhamel method, 2D filter solution can accurately estimate surface heat flux owing to the accounting for lateral heat transfer. The maximum heat flux obtained by the 2D filter solution is 13.6% higher than that obtained by the 1D method [26]. In the present work, six TFTCs deposited on epoxy resin surface