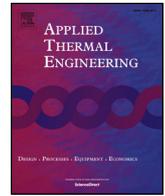




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## Research Paper

## 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.

## ARTICLE INFO

## Keywords:

Cryogen spray cooling  
Surface heat transfer  
Ambient temperature  
Relative humidity  
2D filter solution

## 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 ( $T_a = 10\text{ °C}$ ) 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  $0 \leq r < 2\text{ mm}$  and  $6\text{ mm} \leq r < 10\text{ mm}$  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 and 1.5 ms pulse width is in the range of 3–10 J/cm<sup>2</sup> [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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