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Surface heat transfer characteristics of R404A pulsed spray cooling with an expansion-chambered nozzle for laser dermatology

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ABSTRACT

Cryogen spray cooling is applied to protect epidermis from thermal damage in laser dermatology. However, R134a shows insufficient cooling capacity for minimizing the laser energy absorption by melanin in darkly pigmented human skin. By contrast, the cooling capacity of R404A can be improved with a low boiling point. This study examined the temporal and spatial variations in surface heat transfer during R404A spray cooling using a straight-tube nozzle with an expansion chamber. Substitution of R134a with R404A increases the maximum heat flux by 19%, whereas introducing an expansion chamber enhances the maximum heat flux by 18%. Results indicate that surface heat transfer during R404A spraying exhibits intense temporal and spatial non-uniformity. A sub-region of uniform cooling with a radius of 2 mm appears around the spray center with a high transient heat flux above 300 kW/m^2. This finding can help physicians precisely control the therapy area with enhanced laser energy.

Caractéristiques de transfert de chaleur superficiel du refroidissement par pulvérisation pulsée de R404A avec une tuyère d'expansion-chambrée pour la dermatologie au laser

Mots clés : Refroidissement par pulvérisation ; R404A ; Tuyère d'expansion-chambrée ; Surface de transfert de chaleur ; Dermatologie au laser

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Nomenclature

c	specific heat of substrate (kJ·kg^{-1}·K^{-1})
Nu	local Nusselt number
q	surface heat flux (kW·m^{-2})
Δq	uncertainty of calculated heat flux (kW·m^{-2})
Q	heat extraction per area (kJ·m^{-2})
r	radial distance (mm)
r_s	spray radius (mm)
t	spray time (ms)
Δt	time interval (ms)
T	surface temperature (°C)
T_a	ambient temperature (°C)
ΔT	uncertainty of temperature measurement (°C)
z	axial distance (mm)
Greek	
α	spray angle (°)
Θ	measurement instant (ms)
λ	thermal conductivity of substrate (kW·m^{-1}·K^{-1})
ρ	density of substrate (kg·m^{-3})
τ	normalized time
Subscripts	
boiling	relative to boiling
c	relative to spray center
i	relative to time
max	maximum value
min	minimum value
r	relative to radial distance
sto	stochastic parameter
sys	systematic parameter

1. Introduction

Port wine stain (PWS) birthmark is a congenital vascular malformation that occurs in approximately 0.3% of all newborns (Alper and Holmes, 1983). Based on the principle of selective photothermolysis (Kelly and Nelson, 2000; Kercher et al., 1983), pulsed dye laser with a specific wavelength (typically 585/595 nm) has been the standard treatment for this vascular skin lesion. However, the absorption of laser energy by melanin at these wavelengths can induce unwanted heating of the epidermis, an outcome that may lead to irreversible thermal damage (Chang and Nelson, 1999; Karapetian et al., 2003), especially for darkly pigmented people.

Nelson et al. (1995) proposed cryogen spray cooling (CSC) to reduce the epidermis temperature epidermis, thus allowing for a laser pulse with high energy. Cryogen is spurted in milliseconds on the skin surface, through which superficial layers of the skin (epidermis) can be selectively cooled to minimize or eliminate laser-induced thermal injury (Chang et al., 1998). Non-toxic and environment-friendly cryogen R134a, which has a −26.1 °C boiling point at 1 atm, is currently the only commercial cryogen that assists in laser therapy.

For darkly pigmented skin, the cooling capacity of R134a is insufficient because of its relatively high boiling point. Clinical studies have shown that only less than 20% of patients can achieve complete PWS clearance (Chen et al., 2012). The treatment failure is attributed to the incomplete understanding of the mechanism of interaction between light and tissue. Another factor is the insufficient cooling from cryogen spray, which is especially significant for Asian people because of the strong laser absorption by darkly pigmented skins. Aguilar et al. (2005a,b) proposed the hypobaric pressure method on the skin surface to improve the cryogen cooling capacity. Our recent result (Zhou et al., 2012a) indicated that R134a spray cooling can provide 2.6 times the maximum surface heat flux with a pressure of 0.1 kPa in comparison with the atmospheric pressure at a spray distance of 10 mm. Nevertheless, the implementation of a local vacuum on the epidermis still needs to be developed for clinical applications.

Dai et al. (2006) suggested that R404A with a low boiling point (−46.5 °C at 1 atm) and high volatility is a possible candidate to enhance the cooling efficiency of CSC in clinical application. Zhou et al. (2012b) measured the time-varying R404A spray and observed steady-state spray patterns. The maximum surface heat flux q_{max} can achieve 400 kW/m^2, a result that confirms its better cooling capacity compared with that of R134a (with a q_{max} of approximately 300 kW/m^2). The spray is in a jet-like pattern near the nozzle exit with a high droplet concentration. The effective spray cooling radius of R404A at 50 mm distance is approximately 3 mm, which demonstrates that the R404A spray has better spatial selectivity with a smaller cooling surface than does the R134a spray (corresponding cooling radius = 8 mm). However, few studies are devoted to the transient spray pattern and the radial distribution of surface heat transfer for R404A spray, both of which are closely related to clinical practice.

Optimizing the nozzle design can also increase the heat extraction from skin. The current nozzles used in clinical practice are all straight-tube types, with a nozzle diameter of 0.5–1.4 mm. Sher and Elata (1977) suggested that an expansion chamber can result in efficient atomization at the nozzle exit by enabling a massive flashing process and sufficient time for bubbles to grow. Bar-Kohany and Sher (2004) designed expansion nozzles for diesel spray based on Sher's theory and explored the optimal expansion chamber volume to achieve the highest superheat degree for flash boiling spray. Compared with a straight-tube nozzle, the well-designed nozzle requires lower spray pressure to achieve a comparative atomization effect. Ersoy and Sag (2014) used an ejector as an expansion device instead of an expansion valve in the R134a refrigeration system and improved the coefficient of performance by 6.2–14.5%. Zhou et al. (2014) visualized the internal flow and spray pattern of an expansion-chambered nozzle with different aspect ratios. The atomization effect becomes optimal for CSC when the aspect ratio of the length to the diameter of the chamber ranges from 1:2 to 2:1.