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An experimental study on pulsed spray cooling with refrigerant R-404a in laser surgery

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ABSTRACT

With a low boiling point (−45.5 °C at 1 atm) and high volatility, cryogen R-404a has the potential to replace current R-134a (−26.1 °C at 1 atm) for improved therapeutic outcome of dark skins in cutaneous laser treatment. This paper presents an experimental study on pulse spray cooling with cryogen R-404a including the spray characteristics and the resulting dynamic cooling of a solid surface. The spray system includes a special designed pressure nozzle (with the tube diameter less than 1 mm) that is connected to a fast response electric valve which can open or close within 5 ms. A high-speed video camera is used to obtain images of the spray pattern. The velocity and the diameter of the liquid droplets in spray are measured by the phase Doppler particle analyzer (PDPA). A thin film thermocouple of 2 μ in thickness is directly deposited on the epoxy resin substrate to monitor rapid drop of the surface temperature under the pulsed sprays. The Duhamel's theorem is then solved to obtain the time-varying surface heat flux and heat transfer coefficient of the substrate surface. It is found that the large droplet size together with fairly high-speed in the early jet-like spray leads to highly efficient surface cooling.

1. Introduction

Pulsed Dye Laser (PDL) at wave length of 595 nm or 585 nm has been the common choice for the treatment of vascular skin lesions, such as port wine stain (PWS) [1], based on the principle of selective photothermolysis [2]. The objective of laser treatment for PWS is to cause selective thermal damage to subsurface targets (chromophores) without causing damage to the overlying normal epidermis [3]. However, melanin in epidermis is able to absorb laser energy greatly. The existence of melanin in epidermis causes two side effects in laser surgery of PWS. On one hand, it reduces the amount of the laser energy which reaches diseased blood vessels and negatively influences the therapeutic outcome; on the other hand, the heat absorbed by melanin will cause irreversible thermal damage to the normal epidermis. Cryogen spray cooling (CSC) with cryogen R-134a (−26.1 °C boiling point at 1 atm) may selectively cool the superficial layers of skin to minimize or eliminate laser-induced irreversible injury to the epidermis [4–6]. PDL coupling with CSC of R-134a has been the standard treatment for PWS in dermatology. Many studies have been conducted to investigate the heat transfer behaviours of CSC with R-134a [7–11]. However, for darkly pigmented human skins, nonspecific thermal injury occurs even when irradiated at very low radiant exposure due to insufficient CSC-induced heat removal from skin epidermis [12–14]. With a lower boiling point (−45.5 °C at 1 atm) and higher volatility, R-404a is non-toxic and friendly with ozone depletion, CSC with R-404a has the potential to improve therapeutic outcome of dark skins in cutaneous laser treatment [15].

Anvari and his co-workers at Rice University have carried out some studies on the heat transfer characteristics of cryogen spray cooling of R-404a for laser treatment of PWS [15–18]. They used a skin phantom made of epoxy resin to simulate the human skin. A 30-μm diameter type K thermocouple was embedded 100-μm depth below the phantom surface to acquire the temperature change in response to pulse spray of R-404a. They have used a nozzle with an inner diameter of 1 mm and spray distance of 85 mm. A one-dimensional inverse heat conduction problem was solved to estimate the heat removal from the skin phantom during the R-404a spurt. Their study provided the first heat transfer data for R-404a spry cooling, but little information on the dynamics of heat transfer on the cooling surface and no study on the R-404a spray process were obtained.

This paper presents a systematic experimental study of cryogen R-404a spray and pulse spray cooling for application in laser

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