Influence of Nozzle Diameter on Spray Characteristics and Surface Heat Transfer Dynamics in Cryogen Spray Cooling for Dermatologic Laser Surgery

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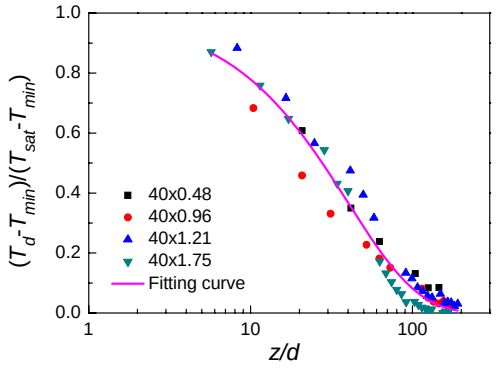
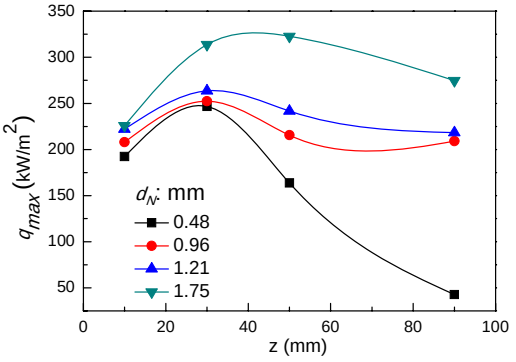
Abstract

Pulsed Dye Laser (PDL) at wave length of 595nm or 585nm has been the common choice for the treatment of vascular skin lesions, such as port wine stain (PWS), based on the principle of selective photothermolysis. 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. However, melanin existing in epidermis will greatly absorb laser energy, which not only negatively influences the therapeutic outcome but also causes irreversible thermal damage to the normal epidermis. Cryogen spray cooling (CSC) with cryogen R-134a (-26.1 ^{o}C boiling point at 1 atm) may selectively precool the superficial layers of skin to minimize or eliminate laser-induced irreversible injury to the epidermis. In order to optimize the nozzle design and enhance their cooling efficiency, an experimental investigation was carried out on the effect of nozzle size on the atomization characteristics and heat transfer dynamics during pulsed cryogen spray cooling using eight straight-tube nozzles with different length and diameter. A phase Doppler particle analyzer (PDPA) is used to measure the droplets diameter and velocity, while a micro-flowmeter is used to monitor the volume flow rate of the pulsed spray. It is found that smaller diameter nozzle presents a better atomization capacity than that with larger diameter. The droplets temperature as a function of spray distance is measured by an inserted micro-thermocouple with a bead diameter of 100 μm. It's found that the temperature of droplets produced by small diameter nozzle deccreases much quickly than that by large diameter nozzle. A thin film thermocouple (TFTC, 2μm) is deposited directly onto the epoxy resin substrate or the so-called skin phantom to measure the surface temperature variations induced by the CSC. An analytical expression based on Fourier's law and Duhamel's theorem is used to calculate surface heat flux from the temperature measurements. It's found that the droplets with high velocity and large diameter produce higher heat flux at the cooling surface. Based on the measurements and calculations, the effect of the eight straight-tube nozzles on the heat transfer dynamics of the cooling surface are comparatively studied and their atomization characteristics are compared. Additionally, the criterion to evaluate the cooling efficiency of different nozzles is proposed, and the variation of heat extraction from the cooling surface with different spray distance by different nozzles is given. The results can be used to guide the selection of nozzles during cryogen spray cooling.



Variation of average non-dimensional temperature of droplet with the non-dimensional axial distance along the centerline



Variation of the maximum surface heat flux with the spray distance for different diameter nozzles.