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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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Nomenclature

T_s	surface temperature (°C)
T_c	cryogen droplets temperature in spray (°C)
q	surface heat flux (kW/m^2)
q_c	maximum of the surface heat flux (kW/m^2)
h	surface heat transfer coefficient (kW/m^2 K)
h_{max}	maximum of the surface heat transfer coefficient (kW/m^2 K)
κ	heat conductivity (kW/m K)
ρ	density (kg/m^3)
c	specific heat capacity (kJ/kg K)
t	time (ms)
Δt	spray duration (ms)
τ	time step
z	spray distance (mm)
D_{10}	arithmetical mean diameter of droplet (μm)
D_{32}	Sauter mean diameter of droplet (μm)

treatment of PWS. A well-controlled spray system was constructed that can accurately control the spray duration from 5 ms to tens of seconds. A high-speed video camera was used to obtain images of the spray pattern during spray. The velocity and the diameter of the liquid droplets in spray were measured by the phase Doppler particle analyzer (PDPA). The droplet average temperature in spray was achieved using the small thermocouples with bead diameter of 100 μ. An epoxy resin substrate was used as a skin phantom. A thin film thermocouple of 2 μ in thickness was deposited directly on the epoxy resin substrate to monitor rapid drop of the surface temperature under the pulsed spray. The dynamic variation of the heat flux and corresponding heat transfer coefficient can then be estimated from the measured temperature data using the Duhamel's theorem.

2. Experimental system and numerical methods

2.1. Spray system

Fig. 1 shows a schematic of the experimental system for flashing spray study. The system consists of a pressure vessel for storage of cryogen, a three-dimensional translational electric position stage (WN105TA300M by Beijing Winner Optics Instruments Co., China) with space resolution of 8 μm, a solenoid electric valve (B2021SBTTO24DVC by Gems, USA) that can open or close within 5 ms, and a specially-designed nozzle. The vessel is a commercial R-404a (Dupont) cryogen container and is pressurized at the saturation pressure of this cryogen at room temperature (1.25 MPa at 25 °C). The valve is installed in the position stage, which controlled by the computer can exactly adjust the position of the nozzle in three dimensions. The geometry of the nozzle resembles that of commercial nozzles used for cryogen spray cooling in conjunction with dermatological laser treatments, which is made of a stainless steel tube of length of 63.5 mm and inner diameter of 0.81 mm and fits tightly into the opening of the solenoid valve. A standard high-pressure hose connects the cryogen vessel to the valve.

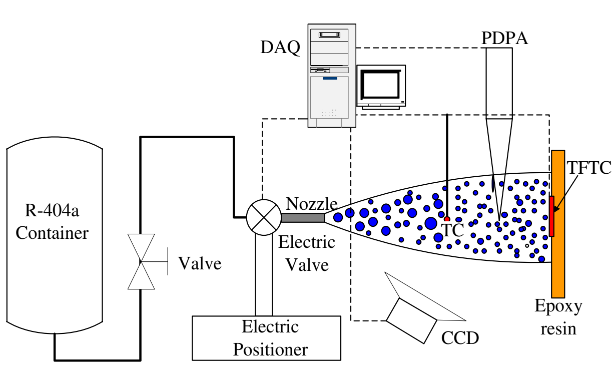

Fig. 1. Schematic of the experimental system.

2.2. Spray characteristics measurement system

A high-speed video camera (MotionXtra HG-100) with shutter speed of 997 μs is used to take photographs of the spray. A PLS-SXE300 Xe lamp with high power provides illumination for the high-speed camera. The camera and the lamp are positioned in the same horizontal plane, with the camera viewing perpendicularly to the spray axis and all pictures are taken at the speed of 1000 fps and the same pixel resolution of 1504 × 1128. The camera is placed either 1900 mm or 500 mm from the spray axis. At a far distance, the camera can catch a view of entire spray; while at a close distance, the camera can take a photo of the spray near the nozzle tip. The two distances give the fields of view of about 1900 × 1400 mm^2 and 500 × 375 mm^2, respectively.

A phase Doppler Particle Analyzer (PDPA by TSI, USA) is used to measure the velocities and diameters of the droplets in the cryogen spray of R-404a. The PDPA generates four interfacing laser beams of different wavelengths, which focus on a probe volume, typically smaller than 1 mm^3. When droplets go through the probe volume, these beams are interfaced and a Doppler signal with a frequency shift proportional to the droplet velocity is generated. The phase difference between the signals collected by adjacent detectors is proportional to droplet diameter. Before taking the measurements, the optimum values of the PDPA parameters had to be selected including the diameter range, velocity range and the laser power. For each measurement, the spray duration lasts 10 s.

2.3. Temperature measurements

A standard type-T thermocouple (Omega, USA) with bead diameter of 100 μm is inserted to the spray to measure the average temperature of cryogen in spray at various radial locations and axial distances. Since the estimated response time of the thermocouple is fairly long, about 10 ms, a steady state cryogen temperature of spray was obtained.

A thin film type-T thermocouple (TFTC) of 2 μ in thickness is deposited directly on the epoxy substrate (50 mm × 50 mm × 5 mm) to monitor the rapid change of the surface temperature during a pulsed spray. The reason for choosing epoxy resin as the cooling substrate is that its thermal property resembles that of human skin. The response time of TFTC is estimated to be about 1.2 μs, which is fast enough to measure the rapid change of the surface temperature [19]. Therefore, the TFTC sensor indeed provides 'real-time' surface temperature measurements. For detail information of the method of surface temperature measurement using TFTC, please refer to our previous work reported in the literature [19].

For surface temperature measurements in pulse spray, both the solenoid valve and the thermocouple are connected to the computer and controlled through a Labview control system. The thermocouple measurements is acquired at 100 kHz and converted to the temperature data using a DAQ board (NI: M-6251). During experiments, the spray duration was first set in the Labview controlling panel. When the valve was turned on, the temperature data from TFTC was acquired simultaneously.

Separate experiments have to be carried out to take high-speed photographs of the spray, to make the PDPA measurements, and