Influence of Cryogen Spray Cooling Parameters on the Heat Extraction Rate from a Sprayed Surface

Emil Karapetian[a], Guillermo Aguilar[b,c], Enrique J. Lavernia[a,b] and J. Stuart Nelson[b,c]
[a]Department of Chemical Engineering and Material Sciences, UC, Irvine, CA 92697
[b]Center for Biomedical Engineering, UC, Irvine, CA 92612
[c]Beckman Laser Institute and Medical Clinic, UC, Irvine, CA 92612

ABSTRACT

Cryogen spray cooling is used to prevent epidermal thermal damage during port-wine stain laser therapy, despite the limited understanding of the fluid dynamics, thermodynamics, and heat transfer characteristics of cryogen sprays. In recent studies, it has been suggested that the heat flux through human skin could be increased by changing physical parameters such as nozzle-to-skin distance, nozzle diameter, and/or by depositing cryogen in sequential spurts. These changes affect spray parameters such as droplet diameter, velocity, and spray temperature. Therefore, in order to optimize new nozzle designs, it is necessary to explore the influence that these fundamental spray parameters have on heat extraction.

In this paper, various valve/nozzle configurations were characterized. A Phase Doppler Particle Analyzer was used to determine the average diameter, velocity, and droplet concentration of various cryogen sprays. The mass flux delivered by each valve/nozzle configuration was also measured, along with the average spray temperature. A custom-made device consisting of an insulated metallic disk was used to measure the heat extracted by different sprays. The results showed that there are significant differences in the heat extracted by the different valve/nozzle configurations. These variations are proportionally influenced by mass fluxes. Strong correlations were also observed between average droplet velocities and heat extraction. These findings indicate that mass flux has a dominant effect on heat extraction from human skin during cryogen spray cooling. It is also apparent that kinetic and thermal energies are other parameters to be considered when optimizing heat extraction.

Keywords: spatial selectivity, port-wine stain, heat extraction rate, nozzle design

1. INTRODUCTION

During dermatologic laser treatments of vascular lesions, such as port-wine stains (PWS), light-absorbing melanin in the epidermis poses two obstacles. First, a significant portion of the energy from the laser pulse is absorbed by the epidermal melanin, potentially causing thermal damage to the epidermis, and second, light absorption in the epidermis results in less energy reaching the target chromophore [1]. Cryogen spray cooling (CSC) is used effectively on patients with low melanin concentration (skin types I-IV) to prevent epidermal thermal damage, while allowing sufficient energy to reach the target lesion [2,3,4]. However, CSC fails to provide sufficient thermal protection for patients with darker skin types (V and VI), who have higher levels of epidermal melanin. Therefore, to extend the benefit of CSC to all patients, it is necessary to improve cooling efficiency: this can be achieved by an in depth understanding of the fundamental spray parameters that influence heat extraction from human skin.

In recent studies, it has been shown that heat flux through the skin can be increased by changing parameters such as nozzle-to-skin distance [5] and nozzle diameter [3,6,7] and/or by depositing cryogen in sequential spurts [8]. These changes influence the fundamental spray parameters such as mass flux, average droplet diameter and velocity, droplet concentration and temperature, which in turn affect the heat flux at the skin surface. Therefore, to optimize new nozzle designs, it is necessary to ascertain the spray parameters that have the greatest influence on the overall heat extraction through the skin surface.

In this study, we used six different valve/nozzle configurations to provide a large range of heat fluxes through the surface of a sprayed substrate. To measure the heat extracted, we used a technique that involves a metallic disk embedded in an insulating epoxy [5,8]. The mass flux for each configuration was computed by measuring the mass of cryogen expelled during timed sprays. A Phase Doppler Particle Analyzer (PDPA) was used to measure droplet size, velocity, and concentration. The spray temperature was measured using a small thermocouple placed in the center of the spray cone 60 mm from the nozzle tip. Using these spray parameters, thermal and kinetic energy densities of the spray were computed. The influence of these parameters on the measured heat extraction was studied in detail.

2. EXPERIMENTAL PROCEDURES

2.1 Cryogen Delivery and Nozzle Configurations

A total of four nozzles and three valves were used to select and study six different valve/nozzle combinations. The four nozzles used for this study include: Two commercial cryogen spray nozzles used for laser treatment of vascular lesions and hair removal (ScleroPLUS™, and GentleLASE™, Candela, Wayland, MA), with approximate inner diameters (I.D.) of 0.8 and 0.5 mm, respectively; and two custom made nozzles, narrow and wide, with I.D. of 0.7 and 1.4 mm, respectively. Liquid cryogen (tetrafluoroethane, boiling temperature T_b = –26 °C at atmospheric pressure) was delivered through a standard high-pressure hose connected to a control valve. The container was pressurized at the cryogen saturation pressure (670 kPa at 25 °C). Solenoid valves were used to provide 100 ms spurts.

Two of the three valves tested operate on an open/close only system and, therefore, for a given spurt, each valve/nozzle configuration has only one characteristic mass flux associated with it. By using a voltage controlled analog valve (Parker Hannifin Corporation, Pneutronics Div., Hollis, NH) attached to the GentleLASE™ nozzle, we were able to vary the mass flux ($\dot{m}$) from 45 to 110 g/min. These mass fluxes correspond to the maximum and minimum valve constrictions, respectively. Table 1 provides a detailed description of each valve/nozzle configuration.

2.2 Heat flux measurements

A custom-made device similar to those reported previously [5,8] was designed and built to measure the maximum heat flux ($q_{\max}$), and the total heat removed (Q_{total}) by a 100 ms spurt for all valve/nozzle configurations used in this study. The device consists of a silver disk (3.18 mm diameter, 0.17 mm thickness), thermally insulated by epoxy (k_T=.218 W/m-°K). The top surface of the disk was exposed to the cryogen spray and the temperature of the disk was measured by a type-K thermocouple soldered to the bottom side. The disk temperature was assumed to be uniform due to the high thermal conductivity of silver (k_T = 429 W/m-K). With these temperature measurements, $q_{\max}$ in W/cm^2 was computed by the following equation:

$$q_{\max} = \frac{m_{disk}\, c_{disk} \left| \left(\frac{dT_{disk}}{dt} \right) \right|_{\max}}{A_{disk}} \tag{1}$$

where m_{disk}, c_{disk}, T_{disk}, A_{disk} are the mass (kg), specific heat (J/kg-K), the temperature (K), and the exposed surface area of the silver disk (cm^2), respectively, and $\left| \left(\frac{dT_{disk}}{dt} \right) \right|_{\max}$ represents the maximum rate of temperature change during the spurt.

To compute Q_{total} produced by each valve/nozzle configuration in J/cm^2, we used the following equation:

$$Q_{\text{total}} = \frac{m_{disk}\, c_{disk} \left(T_0 - T_{disk(t=160ms)} \right)}{A_{disk}}, \tag{2}$$

where T_0 is the initial disk temperature and $T_{disk(t=160ms)}$ is the disk temperature 160 ms after the start of the spurt. The latter value of T was chosen because for all the valve/nozzle configurations used in this study, 160 ms was a sufficiently long time where no further variation in the disk temperature was recorded, i.e., where $\frac{dT_{disk}}{dt} = 0$.

2.3 Mass flux measurements

A 12 oz cryogen container was connected to each valve/nozzle configuration listed in Table 1. To compute the mass flux ($\dot{m}$), the valve was opened and cryogen was released continuously for 1-2 min. The times for which the valve remained open and the weight loss of the containers after each spurt were recorded. Three experiments were recorded for each valve/nozzle configuration and good agreement was obtained among all measurements. Considering all sources of error, a 5% uncertainty is estimated for all the values of $\dot{m}$ measured. Since sprays produced by these valve/nozzle configurations reach fully developed conditions within 30 ms [7], it is reasonable to assume that the $\dot{m}$ measured for these continuous sprays are similar to those corresponding to 100 ms spurts.

2.4 Droplet Diameter, Velocity, and Concentration

A Phase Doppler Particle Analyzer (PDPA by TSI Inc, St. Paul, MN) was used to obtain the local average droplet diameter (d), velocity (v), and droplet concentration in droplets/cm^3 ($C_{droplet}$) of continuous cryogen sprays. The PDPA operates by producing a probe volume, typically smaller than 1 mm^3, at the intersection of two off-phase laser beams of the same wavelength. As a droplet passes through the probe volume, the interference fringe pattern produced by intersecting beams is projected onto the off-axis detectors. The frequency shift of the fringe pattern is proportional to droplet velocity and the phase difference between the signals collected by each detector is proportional to droplet diameter. The number of droplets crossing the probe volume is simultaneously recorded to measure $C_{droplet}$. Further details about the operation of this device may be found elsewhere [9]. All PDPA measurements were taken at a distance of 60 mm from the nozzle tip.

2.5 Temperature Measurements

A type-K thermocouple with bead diameter of approximately 0.3 mm and response time of ~ 40 ms (5SC-TT-E-36 by Omega, Stamford, CT) was used to measure local average steady-state spray temperature. The thermocouple was held in place by a thin rigid wire to minimize spray disruption. Since water condensation and freezing on the thermocouple bead could affect temperature measurements, experiments were conducted in a chamber filled with dry air (relative humidity below 5%). Similar to the PDPA measurements, average spray temperatures were taken at a distance of 60 mm from the nozzle tip, a typical distance during CSC laser dermatologic surgery.

2.6 Kinetic and Thermal Energies

Using the parameters described above, the local (within the 1 mm^3 probe volume of the PDPA) kinetic and thermal energy densities were computed. The kinetic energy density (KE_D) is given by,

$$KE_D = \frac{\pi}{12} d^3 \rho_{cryo} v^2 C_{droplet}, \tag{3}$$

where the ρ_{cryo} is the density of saturated liquid cryogen at ambient temperature and saturation pressure in kg/cm^3. The thermal energy density (TE_D) is defined as:

$$TE_D = \frac{\pi}{6} d^3 \rho_{cryo} c_{cryo} C_{droplet} \left(T_{spray} - T_0\right), \tag{4}$$

where c_{cryo}, and T_{spray} are the specific heat of saturated liquid cryogen at ambient temperature and pressure in J/kg-°C, and the temperature of the spray, respectively. T_0 is the initial temperature of the cryogen defined as the boiling temperature at ambient pressure ($T_b = -26$°C). The thermal energy density is the amount of thermal energy stored by liquid cryogen droplets within a unit volume directly above the surface being cooled.

3. RESULTS

3.1 Heat Flux

Figure 1 shows the maximum rate of temperature change, $\left|\left(\frac{dT_{disk}}{dt}\right)\right|_{\max}$, for the wide (W) nozzle and the GentleLASE™ (GL) nozzle controlled by the analog valve at 3.83 V. These valve/nozzle configurations produced the largest and smallest $\left|\left(\frac{dT_{disk}}{dt}\right)\right|_{\max}$, respectively, of all the valve/nozzle configurations.

Figure 2 illustrates mass flux ($\dot{m}$) and total heat removed (Q_{total}) by each valve/nozzle configuration. The Q_{total} ranges from 0.8 to 2.4 J/cm^2. The Q_{total} measurements show the total heat extracted by a 100 ms spurt if sufficient time was allowed for all the heat extraction by a single spurt to occur.

3.2 Mass Flux

As seen in Figure 2, $\dot{m}$ varies by a factor of 3. A factor of 3 variation was also seen in Q_{total} amongst all the valve/nozzle configurations. The maximum heat flux (q_{max}), however, varies by a factor of 11 for the valve/nozzle configurations used for this study. q_{max} is the focus of this study due to its importance in CSC during port-wine stain laser therapy. Figure 3 shows q_{max} and $\dot{m}$ produced by the GentleLASE nozzle at the two different voltages applied to the AV. Using this approach, we see that q_{max} also varies proportionally with $\dot{m}$.

Figure 4a* illustrates $\dot{m}$ as a function of q_{max}. This figure displays a trend of increasing q_{max} with an increase in $\dot{m}$. The lowest value of $\dot{m}$ (45 g/min) was delivered by the GentleLASE nozzle with the AV at 3.8 V, and this configuration also produced the smallest value of q_{max} (11.0 W/cm^2). The W nozzle delivered the highest $\dot{m}$ (137 g/min) and also produced the highest q_{max} (128 W/cm^2).

3.3 Droplet Diameter, Velocity, and Concentration

Figure 4b* shows Sauter Mean Diameter (SMD) as a function of the q_{max}. Although, no correlation is apparent between the SMD and q_{max}, the variations in the SMD range from 9 to 17 µm. Although not apparent, for each valve/nozzle configuration and for a fixed distance from the nozzle, there is a large variation in droplet size distribution of as much as 35-40% from the average diameter, with single droplet measurements ranging from less than 1 µm to greater than 50 µm.

Figure 4c* shows average droplet velocity (v) as a function of q_{max}. An increase in v results in an increase in q_{max}. The range of v measured varies from 24 to 47 m/s. Figure 4d* illustrates q_{max} as a function of the droplet concentration ($C_{droplet}$). This figure presents an inversely proportional relationship between q_{max} and $C_{droplet}$, with the latter ranging from 780 to 3000 1/cm^3.

3.4 Temperatures

Figure 4e* shows small variations in temperature relative to the large changes in the heat flux. The temperatures ranged from –52 to –58 °C showing minimal variation relative to other parameters in this study.

3.5 Kinetic and thermal energy densities

Figure 5* shows q_{max} as a function of kinetic energy and thermal energy densities (KE_D and TE_D, respectively) measured in J/cm^3. In Figure 5a, KE_D ranges from 1.5×10^{-7} to 1.4×10^{-6} J/cm^3. The values for KE_D are about two orders of magnitude smaller than the values for TE_D (Figure 5b). The TE_D values are absolute values used due to a consideration in cooling and heat extraction, and range from 9.0×10^{-5} to 6.7×10^{-4} J/cm^3. Some rough correlations between KE_D and the q_{max} are suggested, although more observation points are needed to verify them.

4. DISCUSSION

To study the influence of various spray parameters on surface heat extraction, a sensitive and reliable way to measure the heat removed was needed. In this study, the metallic disk method was used because the high thermal conductivity of silver ensures that the measurements are highly influenced by the surface effects of heat removal making this method very sensitive to changes in heat flux [6]. The disk used is thin (.17 mm) relative to its diameter (3.2 mm) and changes in temperature occur quickly, which makes this method very useful during short timed dynamic experiments. Other substrates used to measure surface heat extraction include an epoxy block [6,10,11] or insulated copper rod [6,12]. The epoxy block has similar thermal properties to human skin and, therefore, provides an excellent medium to estimate the temperature profiles within skin. This method, however, lacks the sensitivity to monitor small changes in heat flux due to the low thermal conductivity of the epoxy, the poor interface between the

* For convenience Figures 4 & 5 present the maximum heat flux (q_{max}), which is the dependent parameter, on the shared horizontal axis.

thermocouple and epoxy, and other factors [8]. The insulated copper rod method can be used effectively only for steady-state measurements of heat flux and heat transfer coefficient.

We observed a three-fold variation in the total heat removed (Q_{total}) and a proportional three-fold variation in mass flux ($\dot{m}$) (Figure 2). The only exception in Figure 2 corresponds to the ScleroPLUS valve/nozzle configuration. We believe this may be due to repairs needed for the valve between experiments with this nozzle, resulting in some inconsistent performance.

For more efficient CSC during laser therapy of PWS, however, the rate of heat removal is crucial. Increasing the rate of heat removal improves spatial selectivity (keeping the epidermis cool, while raising the temperature of the target blood vessels). Faster cooling prevents the temperature reduction caused by CSC to reach the targeted blood vessels. For this reason, the maximum heat flux (q_{max}) measured in W/cm^2 was studied in more detail in this paper.

As shown in Figure 4a, there is a strong dependence of q_{max} on $\dot{m}$. This proportional relationship was also observed in measurements of surface cooling using a water spray [14]. Varying $\dot{m}$ by a factor of three results in a similar variation in Q_{total} (Figure 2) and shows an even larger variation in q_{max} (factor of 11) (Figure 4a). A similar range of values for heat flux was obtained in an earlier study using the insulated copper rod method for narrow and wide nozzles [12].

q_{max} showed no dependence on the SMD (Figure 4b) in the measurements obtained in this study. This may be due to a wide distribution of droplet diameters measured, with diameters varying up to 40% with respect to the average droplet diameter. Large variations in the SMD with modest variation in heat flux were also reported in [11]. More data points and larger variations in the heat flux are necessary to observe any dependencies that may exist.

Larger values of v correlate to greater values for q_{max} (Figure 4c). Similar trends were observed in an earlier study [13] in which the heat flux increased with an increase in droplet velocity. This relationship between droplet velocity and heat transfer coefficient (i.e. heat flux) was also observed in a study on surface cooling with a water spray [14]. This may be due to the ability of faster droplets of the same size to penetrate deeper into the liquid cryogen layer that forms on the skin surface during CSC [6]. It may also be attributable to the effect of the axial velocity transferring to a radial velocity of the liquid cryogen moving over the surface, thus enhancing the convective heat transfer coefficient. Within the confines of the valve/nozzle configurations used in this study, increasing $\dot{m}$ produced higher v. The co-dependence of heat extraction on the two related parameters, $\dot{m}$ and v, should be explored further by producing high velocity sprays with low mass flux, perhaps by using higher pressures.

It was suggested by Pikkula et al. [11] that a higher spray density contributes to enhance heat removal, and can compensate for a smaller average droplet size (also suggested to have a proportional relationship with heat removal). In contrast, Figure 4d suggests a decrease in q_{max} with an increase in spray density (i.e. droplet concentration). As the droplet concentration ($C_{droplet}$) increases, finer, more atomized sprays are expected. The valve/nozzle configurations that produced smaller $\dot{m}$ also produced larger $C_{droplet}$. These conditions produce areas of low velocity and, in turn, produce low heat flux. The trend seen in [11] may be due to the image analysis technique used to estimate the spray density with a reported minimum diameters resolution of 9.5 μm. Due to the large distribution of droplet diameter for each measurement, droplets of diameters less than 3 μm were detected for all valve/nozzle configurations. This may result in a very dense, fine spray field falling below the minimum resolution of the imaging technique used.

Figure 4e shows modest changes in spray temperature, measured at a distance of 60 mm from the nozzle tip for all valve/nozzle configurations. Due to the small variations in the spray temperature seen in the confines of this study, it is clear that the spray temperature does not heavily influence the heat flux values measured. In fact, earlier studies suggest that lowering the spray temperature by changing the nozzle to substrate distance does not necessarily increase heat flux [5,10].

It has been suggested [6] that kinetic energy is an important parameter in CSC due to the buildup of a layer of liquid cryogen that insulated the surface from the cooling spray. Adequate kinetic energy may enable the droplets to break through this layer and elevate the heat flux. Figure 5a shows the computed values for the kinetic energy density (KE_D) and their relationship to q_{max}. Since little correlation was observed between the droplet size and heat flux, the trends seen in Figure 5a are largely driven by the velocity component of kinetic energy. This figure suggests an increase in $q_{\max}$ with an increase in KE_D, although more points are necessary to verify this trend.

No correlation is observed between thermal energy density (TE_D) and $q_{\max}$ (Figure 5b). This is consistent with the lack of correlation between droplet size and $q_{\max}$ (Figure 4b) and the lack of correlation between the spray temperature (T_{spray}) and $q_{\max}$ (Figure 4e). Even if there was a correlation between T_{spray} and $q_{\max}$, it is apparent from Equation (4) that the dependence of $q_{\max}$ on TE_D is largely influenced by the droplet diameter (d). Therefore, for a given valve/nozzle configuration and spray distance, d will have a greater influence on the thermal energy density which could contribute to increasing the heat flux.

5. CONCLUSIONS

In this study, it is shown that the heat extracted from a surface using CSC is proportionally influenced by the cryogen mass flux. A three-fold variation was measured for the total heat removed by a 100 ms spurt amongst all the valve/nozzle configurations, corresponding to a proportional three-fold variation in the mass flux. Even larger variations were observed in the maximum heat flux (factor of 11). Keeping the nozzle geometry constant, it is shown that increasing the mass flux can proportionally increase the heat flux. It appears that the spray parameters that have the largest effect on the heat extraction rate are the mass flux and average droplet velocity, which show a proportional relationship, while an inversely proportional relationship exists between the droplet concentration and the heat flux. No correlation between heat flux and droplet size could be deduced from the measurements obtained in this study. Based on these results, it appears that in order to improve the heat extraction rate of current nozzle designs, one should focus on maximizing the spurt mass flux and the average droplet velocity. The end result of this will be the improvement of CSC, enabling the port wine stain laser therapy for patients with higher melanin concentration.

6. ACKNOWLEDGEMENTS

This work was supported by a research grant from the Institute of Arthritis and Musculoskeletal and Skin Diseases at the National Institutes of Health (AR43419). Institutional support from the Office of Naval Research, National Institutes of Health, and the Beckman Laser Institute and Medical Clinic Endowment is also acknowledged. We also acknowledge a grant from The National Science Foundation for the purchase of the PDPA system (CTS-9901375 to EJL). Helpful discussions with Drs. Bernard Choi, John Viator, and Boris Majaron were highly appreciated.

Nozzle	Nozzle I.D. (mm)	Nozzle Length (mm)	Solenoid Valve
ScleroPLUS™ (SP)	0.8	--	Parker Hannifin Corp., General Valve Division, Series 99 valve
GentleLASE™ (GL)	0.5	25	Parker Hannifin Corp., General Valve Division Series 99 valve
Narrow (N)	0.7	25	Fuel injector
Wide (W)	1.4	25	Fuel injector
GentleLASE™ (GL)	0.5	25	Analog Valve (AV) @ 3.83 V, Parker Hannifin Corp., Pneutronics Div
GentleLASE™ (GL)	0.5	25	Analog Valve (AV) @11.34 V, Parker Hannifin Corp., Pneutronics Div

Table 1: Valve/nozzle configurations used in this study.

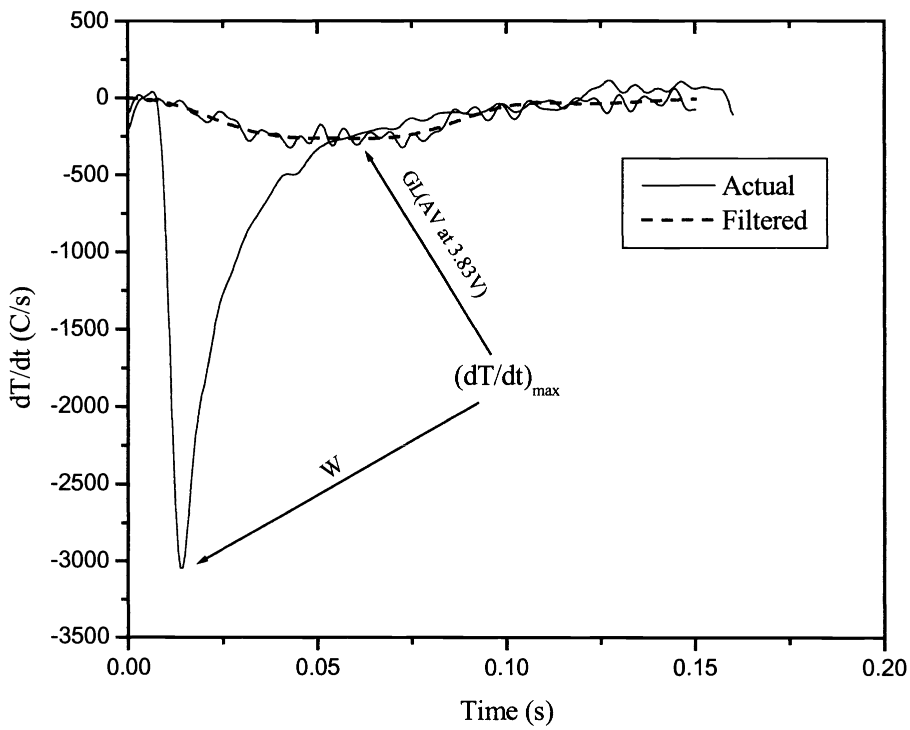

Figure 1: Maximum heat flux $(dT/dt)_{max}$ is shown for the W nozzle and the GentleLASE nozzle used with an AV at 3.83 V as a function of time beginning at the start of a 100 ms cryogen spurt.

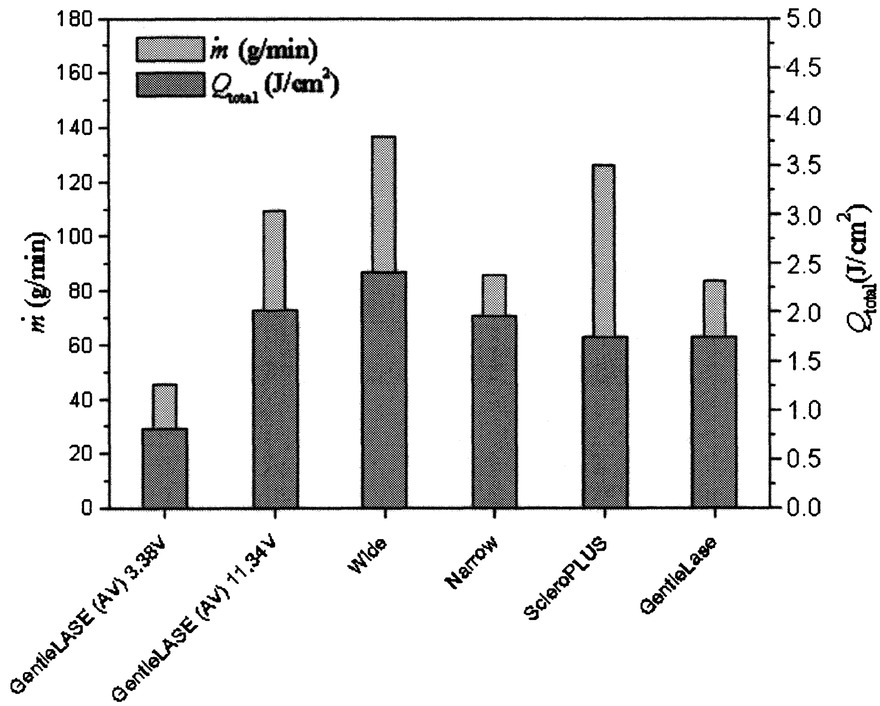

Figure 2: The mass flux and the total heat removed produced by each valve/nozzle configuration.

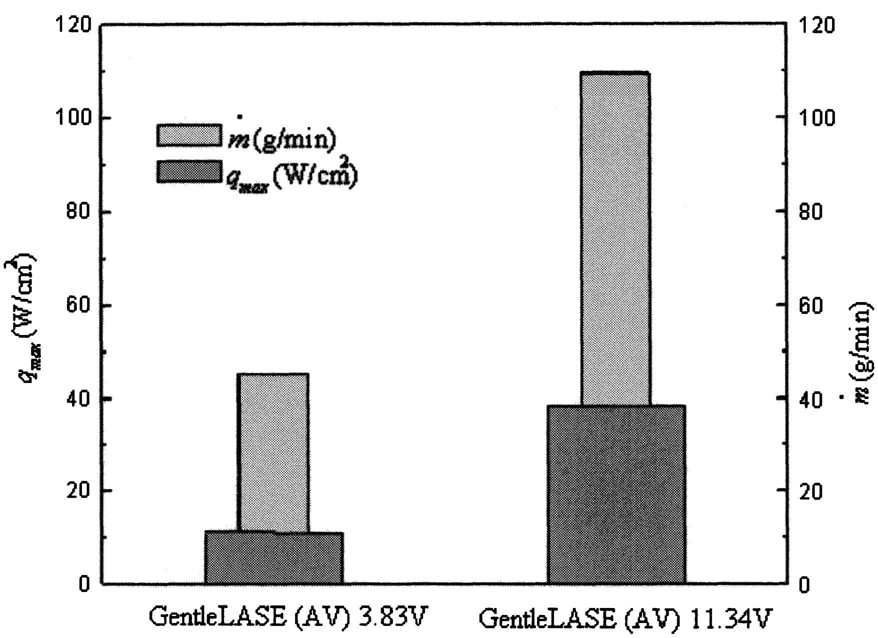

Figure 3: The proportional changes in q_{max} and mass flux are shown for the GentleLASE nozzle with the analog valve (AV) at applied voltages of 3.83 V and 11.34 V.

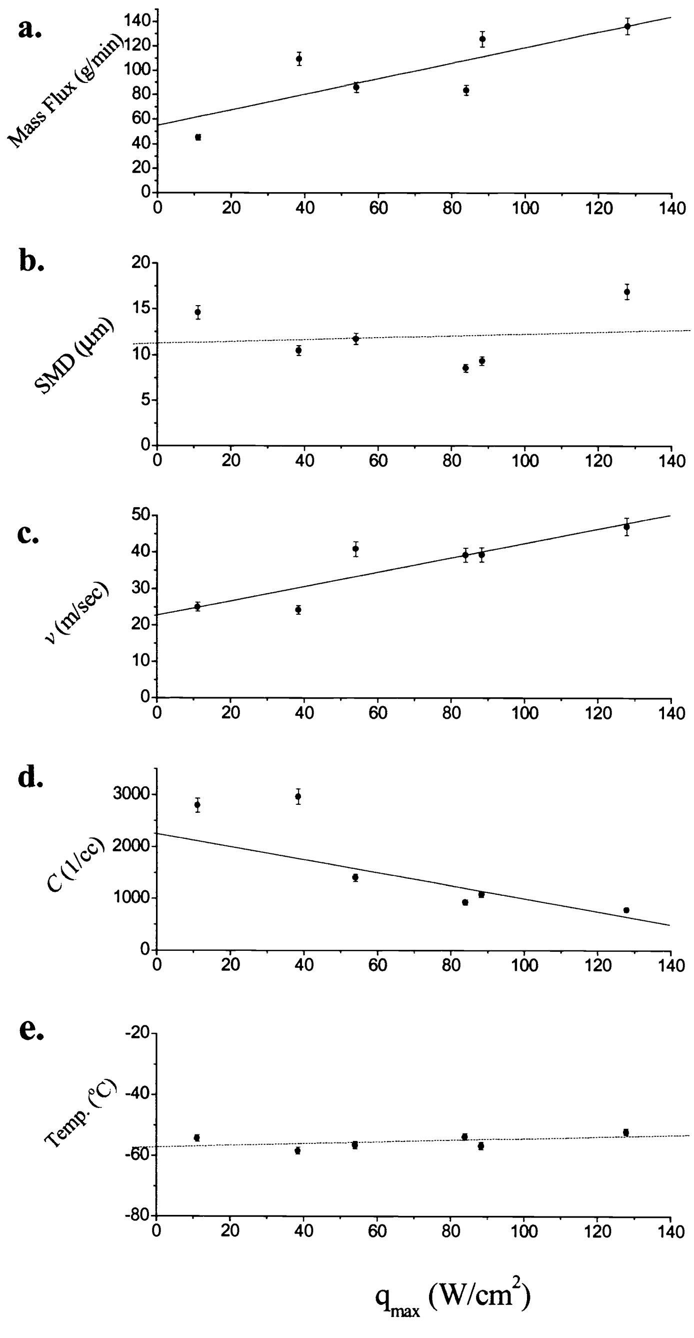

Figure 4: (a) Mass flux, (b) Sauter Mean Diameter (SMD), (c) Average droplet velocity (v), (d) Droplet concentration ($C_{droplet}$), and (e) Average spray temperature are shown as a function of the maximum heat flux ($q_{\max}$). The order of the valve/nozzle configurations labeled in (a) remains the same for all graphs (b-e).

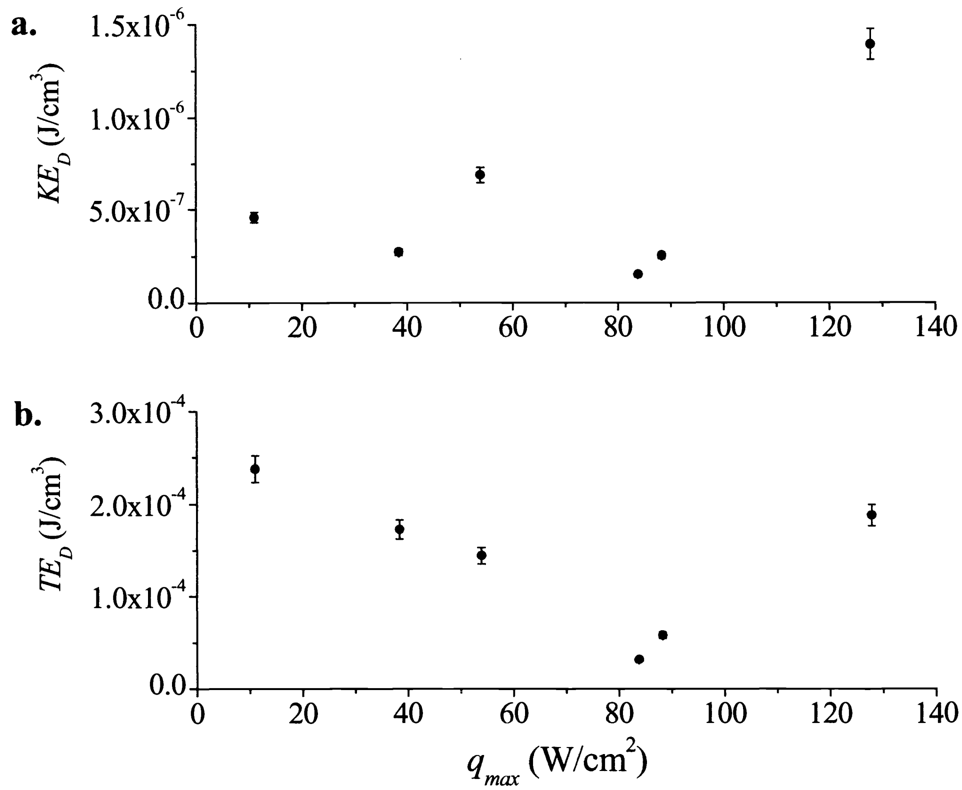

Figure 5: (a) Kinetic energy density (KE_D), and (b) Thermal energy density (TE_D) are shown as functions of the maximum heat flux ($q_{\max}$).

References

1 Chang CJ, Nelson JS. Cryogen spray cooling and higher fluence pulsed dye laser treatment improve port-wine stain clearance while minimizing epidermal damage. Dermatol. Surg.1999; 25: 767-772.

2 Nelson JS, Milner TE, Anvari B, Tanenbaum BS, Kimel S, Svaasand LO, Jacques SL. Dynamic epidermal cooling during pulsed laser treatment of port-wine stain. A new methodology with preliminary clinical evaluation. Arch. Dermatol. 1995; 131: 695-700.

3 Anvari B, Tanenbaum BS, Milner TE, Kimel S, Svaasand LO, Nelson JS. A theoretical study of the thermal response of skin to cryogen spray cooling and pulsed laser irradiation-implications for treatment of port-wine stain birthmarks. Phys. Med. Biol. 1995; 40: 1451-1465.

4 Welch AJ, Motamedi M, Gonzalez A. Evaluation of cooling techiniques for the protection of the epidermis during Nd:YAG laser irradiation of the skin. Nd-YAG Lasers in Surg. and Med. 1983; New York: Elsevier.

5 Aguilar G, Majaron B, Pope K, Svaasand LO, Lavernia EJ, Nelson JS. Influence of nozzle-to-skin distance in cryogen spray cooling for dermatologic laser surgery. Lasers in Surg. and Med. 2001; 28: 113-120.

6 Verkruysse W, Majaron B, Aguilar G, Svaasand LO, Nelson JS. Dynamics of cryogen deposition relative to heat extraction rate during cryogen spray cooling. Proceedings SPIE 2000; 3907: 37-58.

7 Aguilar G, Majaron B, Verkruysse W, Nelson JS, Lavernia EJ. Characterization of cryogenic spray nozzles with application to skin cooling. Proceedings of the ASME 2000; Fluids Engineering Division: 189-197.

8 Majaron B, Aguilar G, Basinger B, Randeberg LL, Svaasand LO, Lavernia EJ, Nelson JS. Sequential cryogen spraying for heat flux control at the skin surface. Proceedings SPIE 2001; 4244: 74-81.

9 Bachalo WD, Houser MJ. Analysis and testing of a new method for drop size measurement using laser light scatter interferometry. Prepared for National Aeronautics and Space Administration, Lewis Research Center under contract NAS3-23684.

10 Torres JH, Nelson JS, Tanenbaum BS, Milner TE, Goodman DM, Anvari B. Estimation of internal skin temperatures in response to cryogen spray cooling: Implications for laser therapy of port wine stains. IEEE Journal of Selected Topics in Quantum Electronics 1999; 5, No. 4: 1058-1065.

11 Pikkula BM, Torres JH, Tunnell JW, and Anvari B. Cryogen spray cooling: effects of droplet size and spray density on heat removal. Lasers in Surgery and Medicine 2001; 28: 103-112.

12 Aguilar G, Verkruysse W, Majaron B, Svaasand LO, Lavernia EJ, and Nelson JS. Measurement of heat flux and heat transfer coefficient during continuous cryogen spray cooling for laser dermatologic surgery. accepted in Journal of Selected Topics in Quantum Electronics special issue of Lasers in Medicine & Biology February 2002.

13 Anvari B, Pikkula BM, Tunnell JW, Torres JH. Thermal and fluid characteristics during cryogen spray cooling. Proceedings SPIE 2001; 4244: 105-112.

14. Schmidt J, Boye H. Influence of velocity and size of the droplets on the heat transfer in spray cooling. Chem. Eng. Technol. 2001; 24: 255-260.