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Atomization and surface heat transfer characteristics of cryogen spray cooling with expansion-chambered nozzles

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ABSTRACT

Cryogen spray cooling (CSC) is commonly applied in laser dermatology to protect the epidermis from thermal damage. Many efforts have attempted to improve the cooling capacity of CSC, among which the use of expansion-chambered nozzles is an effectively simple method with considerable potential. This study examined the influences of the expansion-chambered nozzle structure, including the ratios of inlet nozzle diameter to discharge nozzle diameter and of chamber diameter to discharge nozzle diameter on R134a and R404A spray cooling. Fifteen transparent expansion-chambered nozzles with the expansion chamber aspect ratio of 1.0, chamber diameter to discharge nozzle diameter ratios of 5.0–10.0, and inlet nozzle diameter to discharge nozzle diameter ratios of 0.6–1.4 were tested. The internal flow pattern inside the expansion chamber, external spray pattern, and surface heat transfer characteristics of cryogen spray using different nozzles, including the straight-tube nozzle, were investigated. The structure of the expansion chamber was found to have an important effect on the spray patterns and cooling characteristics. The spray radius obviously decreased when the expansion-chambered nozzles were used, and the spray pattern became narrower as the ratio of chamber diameter to discharge nozzle diameter increased. By contrast, the increase in ratio of two nozzle diameters enlarged the spray radius. Surface temperature and heat flux with different nozzles and cryogens showed a similarity, and correlations of surface temperature and heat flux were proposed. The introduction of expansion-chambered nozzles could effectively improve the spray cooling capacity. The minimum average surface temperature during the fully developed spray period could be reached for both R134a spray and R404A spray by an expansion-chambered nozzle with a chamber diameter to discharge nozzle diameter ratio of roughly 5.0 and an inlet nozzle diameter to discharge nozzle diameter ratio of roughly 0.6.

1. Introduction

Cryogen spray cooling (CSC) with R134a is commonly applied in laser dermatology to protect the epidermis from thermal damage, especially in the treatment of port wine stain (PWS) [1]. Given the lack of effective cooling [2], irreversible thermal damage to the epidermis could occur because of the competitive absorption of laser energy between the epidermal melanin with oxyhemoglobin in the disordered vessel to the selected wavelength (typically pulsed dye laser at 585/595 nm). Since CSC was first suggested for epidermis protection by Nelson [3], much effort has been devoted to the factors that affect spray cooling characteristics, including spurt duration [4], spray distance [5,6], spray angle [7], mass flow [8], and initial temperature of the cooling substrate surface [9].

Although CSC-assisted laser surgery has become the gold standard treatment of PWS, clinical studies showed that only less than 20% of patients can achieve complete clearance [10]. Insufficient cooling is one of the primary reasons, which is particularly significant for people with darkly pigmented skin. To enhance the cooling capacity of CSC, effective methods have been proposed in recent years. Aguilar et al. [11,12] suggested a hypobaric pressure-modulatable technique, in which the spray cooling ability can be enhanced by reducing the spray back pressure. Zhou et al. [13] investigated the effect of hypobaric pressure on the surface heat transfer characteristics of CSC with different cryogens. They indicated that pressure and spray distance should be jointly considered to achieve improved cooling capacity. Moreover, maximum heat flux can be increased 2.6 times for R134a with a pressure of 0.1 kPa and 1.9 times for R404A with a pressure of 1.0 kPa. Dai et al. [14] suggested that the cryogen R404A with a low boiling point (−46.5 °C at 1 atm) and high volatility can be used to reduce surface temperature and enhance heat extraction. Zhou et al.

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Nomenclature

a	thermal diffusion coefficient, $m^2\ s^{-1}$
c	specific heat of substrate, $J\ kg^{-1}\ K^{-1}$
d_c	expansion chamber diameter, mm
d_e	discharge diameter of expansion chamber, mm
d_i	inlet diameter of expansion chamber, mm
q	surface heat flux, $kW\ m^{-2}$
r_s	spray radius, mm
t	time, ms
t^*	normalized time
T	temperature, °C
T^*	normalized temperature
z	depth distance, mm
Bi^*	spray Biot number
Fo_s	Fourier number
Greek symbols	
λ	heat conductivity, $W\ m^{-1}\ K^{-1}$
ρ	density, $kg\ m^{-3}$
τ	time step
δ	thickness of the substrate, m
Subscript	
max	maximum value
min	minimum value

[15,16] found that R404A spray can produce narrower spray width, smaller cooling spot, faster droplet velocity, and smaller droplet diameter, thereby yielding lower minimum surface temperature and higher maximum heat flux compared with R134a.

To further improve the cooling capacity of cryogen spray, acquiring a deep understanding of atomization characteristics is necessary. The atomization of cryogens in the atmosphere is a typical flashing spray that occurs when a pressurized liquid is jetted out through a nozzle. In this process, bubbles intensively generate and rapidly expand because of the sudden drop of pressure, thereby leading to atomization [17]. In a flashing spray, the evaporation and flow patterns inside the nozzle are essential for the spray characteristics [18]. Therefore, the nozzle structure has an important effect on the flashing spray. Compared with the straight-tube nozzle, the expansion-chambered nozzle can provide more space and residence time for evaporation. The benefit of the expansion chamber on the spray can be traced back to as early as 1901 [19]. A typical nozzle for flashing and effervescent atomization with an expansion chamber is a twin-orifice injector, which consists of an inlet orifice and a discharge nozzle that is separated by an expansion chamber [20]. Many research efforts to optimize the atomizer geometry have been conducted in recent decades [21,22]. The ratio of two orifice diameters (diameter of inlet orifice to diameter of discharge nozzle, d_i/d_e) is important in atomization [19,23]. Zeigerson-Katz et al. [21] found that the optimal ratio of two orifice diameters is between 0.6 and 0.75, and the value of 0.7 was suggested by Rasbkovan [19] for a minimal Sauter mean diameter.

However, the nozzles currently used in CSC are all straight-tube nozzles with diameters of approximately 0.5–1.4 mm. Zhou et al. [24] introduced the expansion-chambered nozzle to CSC and found that a significantly decreased droplet temperature can be achieved at the nozzle exit because of a violent phase change. They also found that large bubbles could form within the expansion chamber. In their work, expansion-chambered nozzles with different chamber aspect ratios ranging from 0.25 to 4.0 were compared, and a ratio of approximately 1.0 was recommended to achieve increased cooling capacity. Further research on the expansion-chambered nozzle for CSC conducted by Wang et al. [25] indicated that the application of an expansion chamber with an aspect ratio of 1.0 can make the spray more concentrated and increase the maximum surface heat flux by approximately 18% compared with that using a straight-tube nozzle.

The expansion-chambered nozzles used in CSC by Zhou et al. [24] are different from the traditional twin-orifice injector. The discharge orifice of the twin-orifice injector is an orifice with a very small aspect ratio. In comparison, the discharge orifice of the expansion-chambered nozzle recommended for CSC is a straight tube, which stabilizes the spray pattern. The introduction of an expansion chamber in CSC spray cooling also focuses on the improving of cooling capacity. However, available literature on the influence of an expansion chamber on spray and heat transfer characteristics remain limited, except for the research on the aspect ratio of expansion chamber conducted by Zhou et al. [26]. The effect of an expansion-chambered nozzle for CSC on spray cooling capacity should be analyzed and the structure of the expansion-chamber nozzle should be further optimized. This approach includes not only the ratio of inlet diameter to discharge diameter but also the ratio of expansion chamber diameter to discharge diameter.

The motivation of this work is to investigate the spray and cooling characteristics of cryogens injected through expansion-chambered nozzles recommended for CSC under atmospheric conditions. The other goal is to find how the inlet nozzle diameter to discharge nozzle diameter ratio and the expansion chamber diameter to discharge nozzle diameter ratio affect atomization behaviors and spray cooling characteristics. The transient internal flow inside the expansion chamber and external spray were recorded, and the relationship between the internal flow and external spray was analyzed. The surface temperature of the cooling substrate with different nozzles was measured during the spray to study the influence factors on the cooling capacity, and optimized structures of expansion-chambered nozzles for CSC were recommended. Considering the enhanced cooling capacity of R404A, both R404A and the currently employed cryogen of R134a were used.

2. Experimental setup and methodology

2.1. Spray system

The schematic of the experimental apparatus is illustrated in Fig. 1. The spray system consists of a pressure vessel for cryogen storage, a fast response solenoid valve (B2021SBTTO24DVC by Gems, USA) with a response time of less than 5 ms, nozzles, and a hose tube to connect the system. A data acquisition card (DAQ) (NI: M-6251, USA) is used to control the solenoid valve and trigger the injection. Cryogens stored in the vessel flow into the nozzle through the solenoid valve and are then atomized when cryogens pass through the nozzle because of the flashing spray [27]. The pressures in the storage tanks correspond to the saturation pressures of the cryogens, which are 0.67 and 1.25 MPa respectively for R134a and R404A, at an ambient temperature of 25 °C.