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EFFECTS OF A WIRE MESH ON DROPLET SIZE AND VELOCITY DISTRIBUTIONS OF CRYOGENIC SPRAYS

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ABSTRACT

Cryogen spray cooling allows removing large amounts of heat in short periods of time. Previous investigations have shown that stainless steel wire meshes placed between spray nozzle and target surfaces effectively increase uniformity in lateral heat extraction while reducing cooling efficiency. In this study we used phase Doppler particle analysis to assess the effect of a wire mesh on the diameter and velocity radial distributions of cryogen droplets and, consequently, on the surface heat transfer. We measured at 40 mm downstream and various radial locations within steady state spray cones from two different nozzles without and with a mesh at two mesh-nozzle distances. Results show that with the mesh, droplets lose velocity and increase in size. The closer to the center of the spray cone the droplets are, the larger the loss in velocity. As a consequence, the radial velocity profile is more uniform relative to that without a mesh.

NOMENCLATURE

D	mean drop diameter
D_o	reference mean drop diameter [μm]
d	nozzle-tube inner diameter [mm]
h	mesh-nozzle distance [mm]
N	narrow nozzle
r	radial coordinate
V	mean velocity
V_o	reference mean velocity [m/s]
$\triangle V$	mean velocity difference
W	wide nozzle
z	surface-nozzle distance [mm]

INTRODUCTION

Cryogenic sprays have become an essential heat extraction technique in many industrial processes and medical procedures, such as electronic cooling and dermatologic laser surgery [1]. In general, uniform surface heat transfer is desired. However, because of the non-homogenous characteristics of sprays, such as droplet size and velocity, there are large lateral variations in heat transfer at the surface during spray cooling. For example, for applications that combine cryogenic spray cooling with laser heating, such as dermatologic laser surgery, non-uniform heat extraction may lead to excessive heating and potential irreversible skin damage at the laser beam periphery.

Recent studies have demonstrated that lateral cooling on a flat Plexiglas surface is only uniform along a 2 mm radius within a 20 mm sprayed surface radius [2], and that passive control of mass deposition by means of a wire mesh significantly amplifies the radius of uniform cooling [3]. Wire meshes were first suggested in dermatologic laser surgery to enhance spray atomization and introduce a passive mass-deposition control [4]. It was found that wire meshes reduce heat extraction efficiency and prolong cooling duration in the center of the sprayed area. Nevertheless, it is not clear how the mesh affects the spray and, thus, the surface heat transfer. The objective of the present study is to investigate lateral variations in the average droplet size and velocity distributions of vertical cryogen sprays due to the placement of a wire mesh at different heights.

EXPERIMENTAL METHODS

A scheme of the experimental set up is shown in Fig. 1. The spray injector and wire mesh were mounted on a BiSlide® positioning system (Velmex Inc., Bloomfield NY) to measure diameter and velocity from the center of the spray cone at 0 mm up to a 3 mm radius.

Spray System

Liquid cryogen R-134a, with a boiling temperature at atmospheric pressure of approximately -26 °C, is delivered to a fuel injector attached to a straight-tube nozzle. We used a 1.4 mm inner diameter (d) and 25 mm length nozzle, to be called wide (W), and a 0.7 mm inner diameter (d) and 25 mm length nozzle, to be called narrow (N).

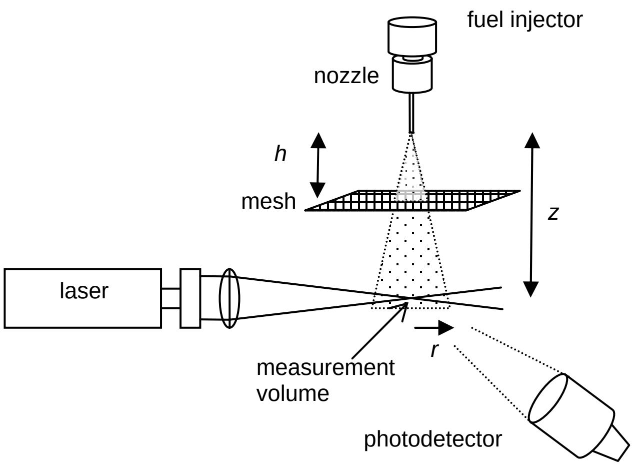

Fig. 1. Experimental set up

Mass Deposition Control

To control the deposition of liquid cryogen, a type 304 stainless steel wire mesh of size 400 (9231744 McMaster-Carr, Los Angeles CA) was placed between the laser volume probe and nozzle tip at h = 5 and 10 mm from the nozzle tip. The size of the mesh is based on the number of openings per inch of wire mesh. The diameter of the steel wire is 25 μm and the opening width is 38 μm. The mesh was allowed to dry before each spurt in order to avoid water condensation and freezing on the mesh which might have affected subsequent measurements.

Phase Doppler Particle Analysis

Phase Doppler anemometry allows measuring simultaneously the size and velocity of individual spherical particles or droplets with high spatial resolution. We used a phase Doppler particle analyzer (TSI Inc., Shoreview MN) to measure and compute the mean diameter and velocity of cryogen droplets at the center of the spray cone and every 1 mm along a 3 mm spray radius. Measurements were taken in steady state at z = 40 mm away from the nozzle. Cryogen sprays for medical applications are commonly applied 30–40 mm from the skin. To quantify the droplet size distribution we used the Sauter mean diameter which also gives information about the quality of atomization [5].

RESULTS AND DISCUSSION

In Figs. 2–5: □, ○, and △ represent results without mesh and with mesh at 5 and 10 mm, respectively; and, horizontal bars on each symbol denote standard deviations. At least four independent measurements were taken at each location. Velocity (V) and diameter (D) are normalized respect to the mean velocity (V_o) and diameter (D_o) at the center of the spray without mesh. It follows that $V' = V/V_o$ and $D' = D/D_o$; where V_o = 55.24 m/s and D_o = 21.78 μm for W; and V_o = 44.42 m/s and D_o = 10.99 μm for N. The radial coordinate (r) is normalized respect to the inner diameter of each nozzle as $r' = r/d$. For simplicity, in the following sections we dropped the primes; that is, V, D and r are dimensionless.

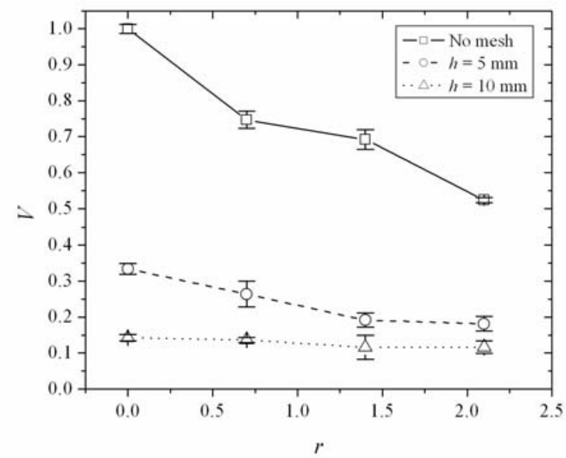

Fig. 2. Radial distributions of V without and with mesh for W. V_0 = 55.24 m/s

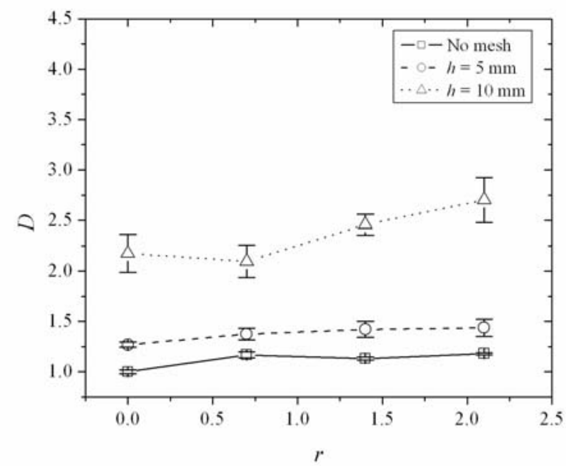

Fig. 3. Radial distribution of D without and with mesh for W. D_0 = 21.78 μm

Wide nozzle

Figure 2 shows radial profiles of V using W. With and without wire mesh, the fastest droplets move by the center of the spray and they travel at lower velocities away from the center. As expected, the wire mesh induces a decline in velocity: for these experimental conditions, V decreases more than 50% at every radial location.

Figure 3 shows radial profiles of D using W. Without mesh, the droplet size slightly increases from the spray center to the periphery. With the mesh at h = 5 mm: the droplet size also increases from the spray center up to $r \approx 2.14$; at each radial location there is an ≈ 25% increment in D respect to the case without mesh. With the mesh at h = 10 mm: the droplet size shows an overall tendency to increase from the spray center to the periphery. Droplets are bigger at each radial location than those with mesh at h = 5 mm and without mesh.

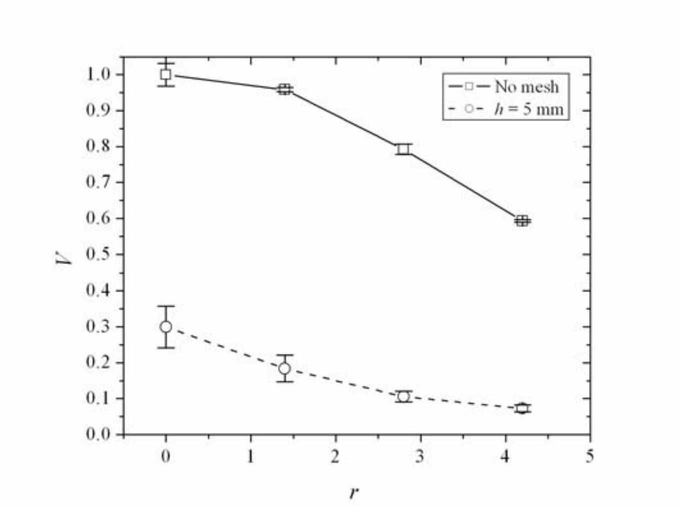

Fig. 4. Radial distribution of V without and with mesh for N. V_0 = 44.42 m/s

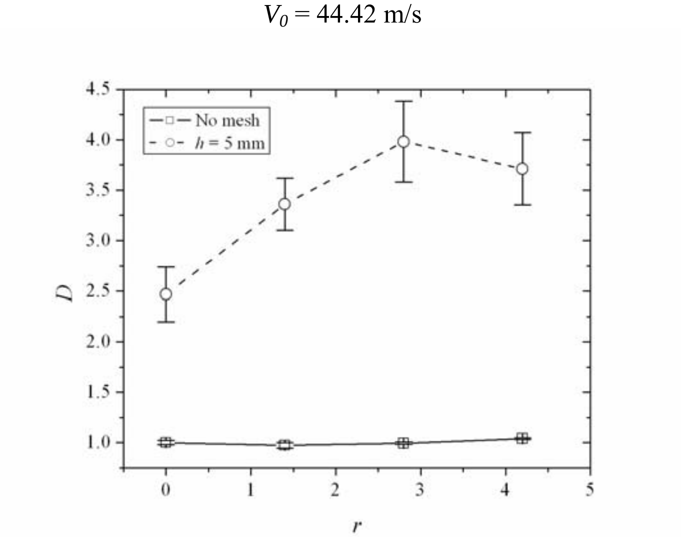

Fig. 5. Radial distribution of D without and with mesh for N. D_0 = 10.99 µm

Narrow nozzle

Figure 4 shows radial profiles of V using N without and with mesh at h = 5 mm only. A steady state spray with the mesh at 10 mm was never established because the spray itself blocked the mesh. As opposed to the spray from W, this spray exhibited smaller and slower traveling droplets. Consequently, the liquid cryogen eventually accumulated on the mesh surface and started to drip as a cascade of droplets. This phenomena did not occur at h = 5 mm. As with W, velocities decrease from the center of the spray to the periphery and the wire mesh induces a decline in V of more than 50% at each radial location.

Figure 5 shows radial profiles of D using N. Without mesh, the droplet size remains unchanged within a 3 mm radius. Comparing the curves without mesh in Figs. 2 and 3 to those in Figs. 4 and 5, respectively, and regarding that V_o = 55.24 m/s and D_o = 21.78 µm for W while V_o = 44.42 m/s and D_o = 10.99 µm for N, measurements show that the spray from N was better atomized, more homogenous and slower than that from W, as already mentioned and expected. With the mesh, it seems as if the droplet size increases from the center to the periphery. Nevertheless, it is evident that the droplet size at every radial location increases using the mesh as opposed to not using it.

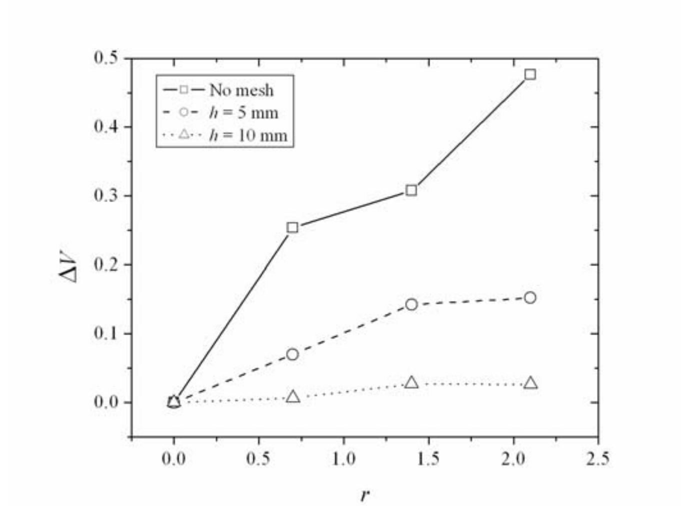

Fig. 6. Radial distribution of $\triangle V$ without and with mesh for W.

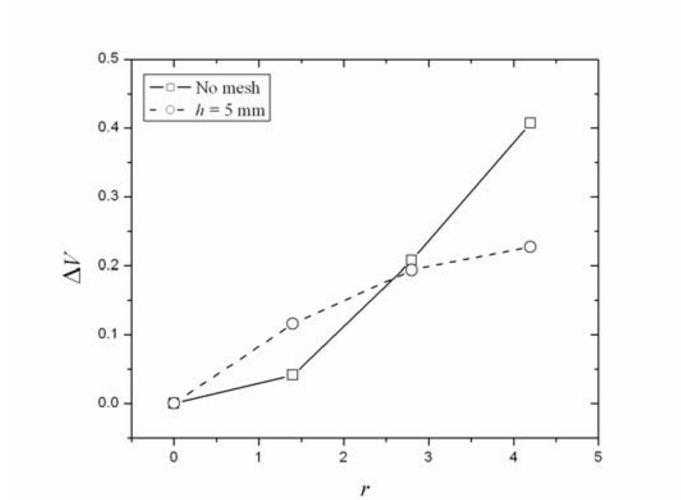

Fig. 7. Radial distribution of $\triangle V$ without and with mesh for N.

Uniform radial distributions of *V*

The difference in velocity ($\triangle V$) between the center and other radial locations is smaller with the mesh than without it, as shown in Figs. 6 and 7. $\Delta V(r_i) = |V(0)-V(r_i)|$, where i = 0, 1, 2 and 3. This is because the higher the impact velocity on the mesh surface is the larger the decline in velocity. The smallest ΔV occurred with the mesh at 10 mm.

Discussion

In previous investigations our research group studied the surface heat transfer on skin phantoms during cryogen spray cooling with passive mass deposition control by wire meshes. Vu *et al.* [4] used the same two nozzles (N and W), meshes of various sizes and 50 ms spurt durations to extract heat from a skin phantom with a surface thermal sensor. The authors found that wire meshes reduced the maximum heat flux and, consequently, the cooling efficiency for both nozzles; however, for the larger diameter nozzle, cooling duration was prolonged significantly when compared to the case without a mesh, which led to an increase of heat removal (defined as the time integral of the surface heat flux). Franco *et al.* [3] used the W nozzle, a 400 size mesh and 60 ms spurt durations to measure lateral variations in surface heat transfer of a skin phantom. The authors found that more uniform heat transfer in time and space (along the radial coordinate) takes place using the mesh which in addition introduces a thermal delay in cooling. Although we conducted a steady state experiment, our results explain the reported effects of wire meshes on surface heat transfer. It is clear that with meshes, less liquid cryogen is deposited on the surface (since cryogen also evaporates at the mesh) and, consequently, less heat may be removed. Besides mass deposition, the velocity of impingement also plays a fundamental role, as shown by Karapetian *et al.* [6]. The authors found that for fully atomized cryogen sprays the maximum heat flux on the surface of a skin phantom increased as the droplet velocity increased and that the droplet size had a negligible influence. Because the heat transfer is a function of the impact velocity, cryogen droplets impinging onto the surface at lower velocities (with mesh) remove less heat than faster droplets (without mesh). Ciofalo et al. [7] found that the heat transfer coefficient and maximum heat flux depend upon the mass flux and droplet velocity, while the droplet size had a negligible influence. The reduction in velocity also explains the thermal delay seen by Vu *et al.* [4] and Franco *et al.* [3]. The prolonged cooling may be a consequence of droplets being deposited over a relative larger period of time because of the loss in velocity. In addition, the mesh induces more uniform lateral heat transfer since the difference in impinging velocities between radial locations also decreases, as shown in Figs. 6 and 7.

Results show that using either the W or N nozzle with and without a mesh, the Sauter mean diameter tends to grow with radial distance from the center. This trend may be attributed to collision effects, vortex effects and evaporation effects. Wu et al. [8] suggested that droplet growth with radial distance from the center can be attributed to the shear experienced by the spray periphery: the outer layer of the jet has a lower velocity than the central region, as droplets move from the center to the periphery due to shear forces, collisions between droplets become more frequent. Another possible mechanism, suggested by Kosaka et al. [9], is that large droplets are easily centrifuged to the periphery because of large-scale vortices in the spray tip region. Finally, the evaporation rate of cryogen droplets may be a function of velocity: high speed droplets by the spray center experience higher evaporation rates than those slow droplets by the periphery of the spray.

Figures 3 and 4 show that the wire mesh increases the Sauter mean diameter respect to the no mesh case, which means that the ratio of volume to surface area of the spray increased yielding a coarser spray. A possible mechanism for the growth of droplets is collision effects because droplets are not only moving primarily in the direction of the jet but in other directions too: the mesh introduces a disturbance in the traveling direction of the droplets increasing the probability of collisions and, consequently, coalescence. At 5 and 10 mm from the tip the cryogen is still a liquid jet; therefore, drops are formed because of the shear stresses between liquid and gas and the sudden jet break-up at the mesh, which introduces new directions of traveling.

CONCLUSIONS

Mass-deposition control through a wire mesh reduces the velocity of droplets but induces a more uniform radial distribution of velocities, allowing uniform mass deposition of liquid cryogen. Also, the average droplet size increases. The magnitude of these effects is a function of the nozzle and mesh geometry and the mesh-nozzle distance *h*. For long cryogen spurts (>1 s) and fine sprays (D_o < 15 µm), *h* plays a fundamental role since the liquid cryogen may accumulate on the mesh.

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