# MULTIPLEXED ELECTROSPRAY SCALING FOR LIQUID FUEL INJECTION

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**Abstract:** We present a model predicting the maximum flow density within a minimum evaporation length for a liquid fuel injector using multiplexed electrospray (MES) for compact combustion applications. This work reveals the influence that the level of multiplexing, droplet diameter and surrounding gas temperature has on the size and performance of microfabricated MES fuel injectors which ensure complete evaporation while overcoming space-charge effects. The maximum flow density is shown to increase by 74X while the evaporation length decreases by 4X for a 20˚C change in the surrounding gas temperature and over the range of theoretical minimum droplet diameters of 4µm-7µm for ethanol.

**Keywords:** microcombustion, electrospray, fuel atomization

## INTRODUCTION

Liquid fuel injection strategies are critical to the design of small-scale portable power systems based on the combustion of liquid hydrocarbons. Combustion-based devices take advantage of the significantly higher energy density available in liquid hydrocarbons when compared to conventional batteries (42 MJ/kg for JP-8 diesel fuel versus 0.36 MJ/kg for primary batteries). When scaling down the size of the combustor volume to the $cm^3$ range and below, catalytic conversion and diffusion-controlled combustion will likely be used and require the fuel to be delivered as small and rapidly evaporating droplets [1]. Fuels from biomass such as ethanol or butanol and liquid hydrocarbons such as JP-8, the logistical fuel of choice for the Army, are highly desirable. However, these fuels require atomization techniques to generate sufficiently small droplets. Multiplexed electrospray (MES) have demonstrated to be effective in atomizing liquid fuel into fine droplets enabling meso-scale combustion [1-3].

MES devices (Fig. 1) are typically operated in cone-jet mode by applying a large voltage between the fluid ($V_1$) contained in nozzles and the extractor electrode ($V_2$) to create mono-dispersed charged droplets. A second potential between the extractor electrode ($V_2$) and collector (electrical ground) is applied to maintain a droplet trajectory away from the extractor surface and towards the collector spaced at a distance of *d*. In spray combustion the combustion can take place either directly between the extractor layer and the grounded mesh or in a downstream combustion region. For compact catalytic combustion applications the combustion will take place on the surface of the grounded collector such as demonstrated in [1] or immediately downstream.

A high level of multiplexing is required to achieve a large flowrate, *Q*, while maintaining small, rapidly evaporating droplets (diameter, $D \propto (Q/nozzle)^{1/2 \rightarrow 1/3}$). Although the authors have previously demonstrated microfabrication of MES devices containing 11,547-nozzles/$cm^2$ [2], the level of multiplexing is practically limited by space-charge effects and requires strong counteracting removal fields; $V_2/d$ [3]. When considering evaporation requirements and space-charge effects for MES devices three key parameters can be isolated: (1) l*evel of multiplexing:* limited by space-charge, but necessary for small droplet diameters; (2) d*roplet diameter:* decreased diameter enables fast evaporation, but limited by geometry and level of multiplexing; and (3) t*emperature:* enables faster evaporation, however requires power for pre-heating or reduces potential power density delivered to IC-engines.

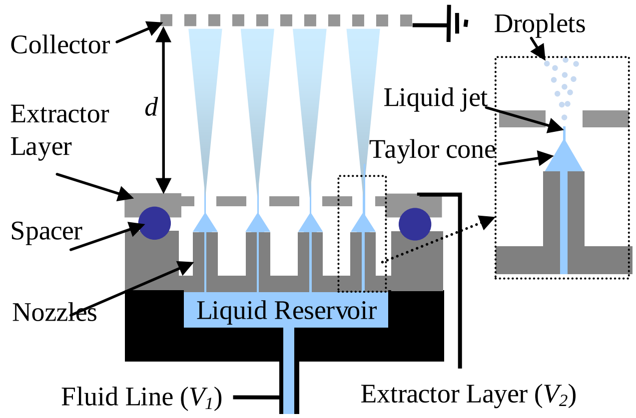


*Fig 1. Schematic cross-section of an MES device.*

In this work, a $D^2$-law evaporation model is combined with the minimum driving field [3] to investigate the influence that the level of multiplexing, droplet diameter and temperature has on the scaling of MES devices.

## THEORY

### Droplet Evaporation

Evaporation imposes a *minimum* spacing, $d_{min}$, between the device and ground required to ensure complete evaporation of the droplet. The well-known $D^2$-law was used to estimate $d_{min}$ required for a liquid fuel droplet to completely evaporate:

$$d_{\min} = D_0^2 v_{drop} \big/ K_{evap}\,, \tag{1}$$

where $D_0$ is the initial droplet diameter, $v_{drop}$ is the velocity of the droplet and the constant $K_{evap}$ is calculated using the diffusion limited process of evaporation [4].

### Space-charge

In contrast to droplet evaporation, space-charge forces exerted on the droplets impose a limitation on the *maximum* spacing $d_{max}$ to ensure adequate removal field strengths. Space-charge exists from the charge associated with each droplet emitted from the device and is dominant in the first millimeter causing satellite droplets to reverse their trajectory and deposit on the surface of the extractor. This eventually leads to flooding and stoppage of fuel injection. The line-of-charge model developed in [3] over-predicts the required removal field, $E_d$ (i.e. $V_2/d$), to ensure all charges will maintain a trajectory towards the collector region, but provides an analytical approximation of the space-charge:

$$E_d = E_0 + C_\infty t(I/A)\left[ n P\big/ d - \frac{1}{2}(n+1)n(P/d)^2 \right]. \tag{2}$$

Replacing $t$ with $d/v_{drop}$ and solving for $d$ Eq. (2) becomes:

$$d_{\max} = \frac{C_\infty (1/\upsilon_z)(I/A)(P^2/2)(n+1)n + V_2}{E_0 + C_\infty (1/v_{drop})(I/A)nP} \tag{3}$$

where $E_0$ is the minimum field required to eliminate satellite trapping for a single spray, $C_\infty$ is a coefficient equal to $0.827/\varepsilon_0$, $I$ is the current for a single electrospray, $A$ is the area per nozzle, $P$ is the pitch between nozzles, and $n$ is the number of concentric hexagonal rings. The key parameters to determine $d_{max}$ for given micromachined geometries using Eq. (3) are $I$, $v_{drop}$, and $V_2$. Both $I$ and $v_{drop}$ are determined through relationships between the flow per nozzle ($Q_{nozzle}$) and $D$. The voltage $V_2$ is determined by the availability of compact, high voltage dc-dc or ac-dc converters. Up to 5 kV can be achieved with a low current draw. A voltage between $V_1$ and $V_2$ of approximately 1kV is typically required to operate in cone-jet mode leaving $V_2$ = 4kV to generate the removal field $E_d$.

### Model Parameter Evaluation

*Droplet velocity*: The velocity of the droplets immediately upstream of the Taylor cone can be approximated as the velocity of the cone-jet ($v_{drop} = Q/(\pi r_j^2)$) using approximations of the jet radius $r_j$ which is a function of both $Q_{nozzle}$ and fluid properties [5]. Downstream of the jet formation region a velocity profile is undertaken by the charged droplets and can be determined predominantly by the space-charge forces and the applied electric field, $E_d$ [6]. The drag forces are negligible compared to the two electrical forces for the air velocity in micro-combustors.

*Electrospray characteristics*: Relationships between $D$, $Q_{nozzle}$, and $I$ have been developed by numerous researchers that are only valid for ranges of viscosity, dielectric constant and conductivity. For the fluids of interest (viscosity >1 cSt, $\varepsilon < 40$, $K < 10^{-4}$) we used the following relationships developed in [7]:

$$I = f(\varepsilon)(\gamma K Q_{nozzle}/\varepsilon)^{1/2}\,, \tag{4}$$

and

$$D = G(\varepsilon)(Q_{nozzle}\varepsilon\varepsilon_0/K)^{1/3}\,, \tag{5}$$

where $\gamma$ is the liquid surface tension and the coefficients $f(\varepsilon) = -449 - 0.21\varepsilon + 157\varepsilon^{1/6}$ and $G(\varepsilon) = -10.9\varepsilon^{-6/5} + 4.08\varepsilon^{-1/3}$ are found empirically in [8].

## RESULTS AND DISCUSSION

*Electrospray characteristics:* The device shown in Fig. 2 developed in our previous work [2] was used to provide estimations of the spray velocity and the $Q_{nozzle}$–$D$ relationship using a Phase Doppler Particle Analyzer from Dantec Dynamics to measure both velocity and droplet diameter. The $n$=2, 19-nozzle device had nozzle outer and inner diameters of 90 µm and 45 µm respectively, a nozzle height of 240 µm, a nozzle pitch of 300 µm, and a nozzle-to-extractor spacing of 180 µm.

Fig. 2 shows $D$ versus $Q_{nozzle}$ over the flow range limited by space-charge effects ($Q_{nozzle}$ = 0.08-0.22 mL/hour). The relationship developed from Eq. 5 is also plotted showing good agreement for ethanol. The electrical conductivity of the ethanol was measured to be $6.2 \times 10^5$ S/m, while the surface tension ($22.3 \times 10^{-3}$ N/m), density (789 kg/m$^3$), and dielectric constant (24.3) were taken from literature. The measurement of $v_{drop}$ was taken starting from 2 mm from the extractor. The initial deceleration due to space-charge within the first millimeter was missed due to our measurement system and therefore our measurements exhibit only the acceleration due to $E_d$ (~$7 \times 10^5$ V/m). The average velocity ranged from 10-20 m/s through the flow range for the 19-nozzle array.

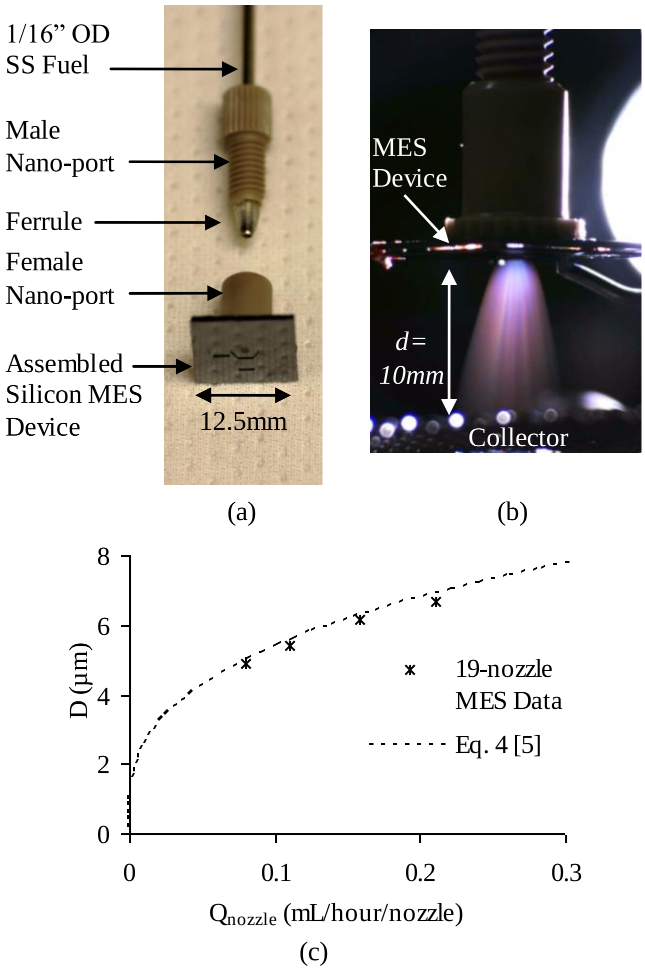


*Fig 2. (a) Photograph of MES assembly components, (b) demonstration of electrospray action and (c) example droplet characteristic measurements.*

Larger levels of multiplexing will cause the deceleration in the initial millimeter to increase and the average $v_{drop}$ can decrease to below 10 m/s as suggested in [1], which provided measurements on devices with a high level of multiplexing. In this work we evaluate the scaling for velocities ranging from 5-15m/s for multiplexed electrospray devices operating at $Q_{min}$ between 0.05 and 0.15 mL/hour.

*Droplet Evaporation*: The $D_{min}$ required to completely evaporate a droplet of ethanol was evaluated (Fig. 3) over a range of surrounding gas temperatures and expected values for $v_{drop}$. This graph suggests that diameters in the range of 3-4 µm are required to ensure complete evaporation at room temperature and to achieve $d$ < 10 mm, while droplets on the order of 6 µm are sufficient at gas temperatures of 50°C. Temperatures can reach greater than 200°C in configurations having a catalyst coated collector due to radiative heating, as demonstrated in [1] and therefore the larger droplet diameters can be handled. However, low temperature fuel injection is desired for

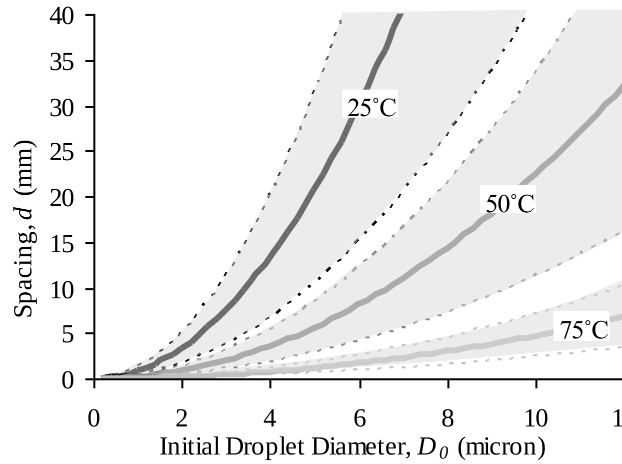


*Fig 3. $D_{min}$ required for complete evaporation versus the initial droplet diameter for ethanol at 25°C, 50°C, and 75°C with velocities of 10 m/s +/- 5 m/s.*

configurations that place the combustion downstream of the collector (i.e. injection into IC engines) in order to maximize the energy density of the fuel/air mixture and keep exhaust recirculation impacts to a minimum.

*Minimum droplet diameter*: Estimation of $D_{min}$ from theoretical models provides only an order of magnitude of the diameter and often provides an overestimation. A $D_{min}$ can be estimated from the different minimum flow rates, $Q_0$ suggested in [5 and 6], which suggest a $Q_0$ ranging from 0.07-0.3 mL/hour and corresponding $D$ of 4.7-7.7 µm. These estimations, however do not consider evaporative loss at the surface of the Taylor cone which may be the practical limit for the minimum sustainable cone. Stable Taylor cones may be possible at lower flow rates if the evaporative surface area of the Taylor cone is reduced. This means decreased nozzle diameters are desirable to achieve low $D_{min}$, and therefore decreasing the spacing required for complete evaporation. In our experiments with 90µm outer diameter nozzles stable electrospray has been achieved at $Q_{nozzle}$=0.04 mL/hour suggesting $D_{min}$ below 4µm is achievable using microfabricated nozzles and axial spacing of combustors below 10 mm at room temperature. It is possible to reduce $D_{min}$ even further by decreasing the nozzle dimensions until practical microfabrication limits are met.

*Space-charge:* The maximum flow density for a multiplexed design will occur at the intersection of the space-charge line (S-C) and the evaporation (Evap.) line as shown in Fig. 4 for a given level of multiplexing. If limited to $D_{min}$ of 6µm as suggested for large nozzle diameters, a multiplexing level of only 1 (7 nozzles/cm$^2$) can be used at a surrounding gas temperature of 30°C. The resulting total flow density is 1.3 mL/(hour·cm$^2$) requiring a spacing

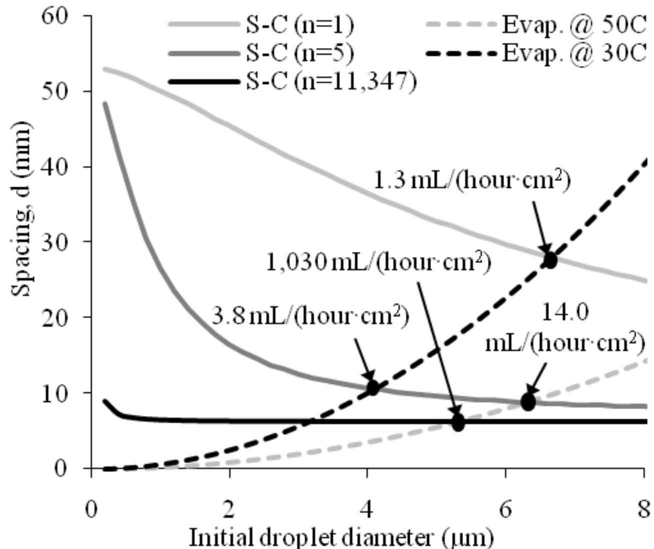


*Fig 4. $d_{min}$ required for complete evaporation (Evap.) and $d_{max}$ required by space-charge (S-C) for 30°C and 50°C ($v_{drop}$=10m/s).*

>32 mm. For a $D_{min}$ of 4µm using microfabricated nozzles, however, a multiplexing level of 5 (91 nozzles/cm$^2$) can be used resulting in a total flow density of 3.8 mL/(hour·cm$^2$) and a spacing of 10.5 mm. If the surrounding gas temperature is increased to 50°C the flow density can be increased to >1 L/(hour·cm$^2$) using a multiplexing level of 61 (11,347 nozzles/cm$^2$), which was demonstrated in [2]. In addition to temperature, a small change in the droplet diameter (< 1 µm) results in a 74X increase in the flow density as shown by the maximum points along the 50°C evaporation in Fig. 4.

The large magnitude change in potential MES flow densities demonstrates the need to decrease $D_{min}$, which may be accomplished by fabricating smaller nozzle diameters to reduce evaporation of the Taylor-cone surface. For demonstrated microfabricated nozzles (11,547 nozzles/cm$^2$) and theoretical $D_{min}$, Fig. 5 suggests small increases in the surrounding gas temperature can result in a significant increase of the maximum flow density. Such small increases in the gas temperature may be accomplished by tapping into the hot exhaust stream with little impact on system performance.

## CONCLUSION

We evaluated the influence of droplet diameter, level of multiplexing, and temperature on the scaling potential of MES devices using a $D^2$-law evaporation model and an analytic model for space-charge. The results shown can be used to design devices that maximize the flow density while minimizing the spacing, *d* and therefore the compactness of the fuel injector for compact combustion applications.

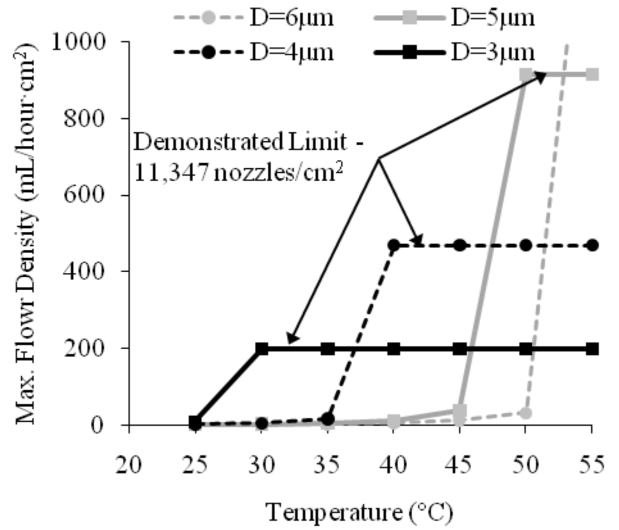


*Fig 5. Maximum flow densities for complete evaporation versus temperature for a span of $D_{min}$ ($v_{drop}$=10m/s).*

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