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THE ROLE OF LIQUID VISCOSITY AND ELECTRICAL CONDUCTIVITY ON THE MOTIONS INSIDE TAYLOR CONES IN E.H.D. SPRAYING OF LIQUIDS

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Electrosprays, applied in a wide and rapidly growing areas from paint spraiying and jet printing to fuel atomization and biotechnology (Bailey, 1988; Fenn et al., 1989), have a number of interesting features which must be considered. For example, liquid motions inside the conical meniscus must be studied to calculate the charge convection along the surface and quantify the relative importance of charge convection as compared to conduction.

Meridional circulation of liquid toward the apex along the generatrix and away from the apex along the axis was firstly reported by Hayati et al. (1986). They pointed out the electrical shear stresses at the cone surface, $\tau_{\theta r} = \epsilon_o(E_\theta^o - \beta E_\theta^i)E_r$, to be the driving force of this motion; E_θ and E_r are the normal and tangential components of the electric field, ϵ_o and $\beta\epsilon_o$ are the vacuum and liquid permittivities respectively and superscripts o and i refer to the outer and inner (liquid) media. This assumption is strongly supported by experiments since when liquids of high enough conductivity are electrosprayed there is no noticeable motion different from the pure sink flow corresponding to the imposed flow rate Q. In these cases, E_r is practically zero and therefore $\tau_{\theta r}$ is negligible. Intense swirl, in addition to the meridional motion, has been also reported by Fernández-Feria et al. (1995) and Shtern and Barrero (1994, 1995a,b) when liquids of sufficiently small electrical conductivity and viscosity, such as heptane and other liquid parafins, are used.

Tangential stresses acting on the liquid surface impose a characteristic velocity U that can be larger or smaller than the sink velocity Q/L_c^2; L_c being the characteristic length of the meniscus: the neddle radius. In effect, viscous and electric stresses at the surface must be balanced, so that

$$\tau_{\theta r} \sim \mu U/L_c \sim \epsilon_o E_n^o E_r,$$

μ being the liquid viscosity. Taking into account that for a conical meniscus of semi-angle α, $E_n^o \sim (\gamma/\epsilon_o r \tan\alpha)^{1/2}$ as given by Taylor and $E_r \sim I/2\pi(1-\cos\alpha)Kr^2$ (assuming that inside the cone the charge is transported by conduction), one easily arrives at

$$\tau_{\theta r} = -\left[\frac{\epsilon_c \gamma I^2}{2\pi^2(1-\cos\alpha)^2 \tan\alpha K^2}\right]^{1/2} r^{-5/2} = -\Gamma r^{-5/2} \quad (1)$$

and

$$U \sim [\gamma\epsilon_o I^2/(L_c^3 K^2 \mu^2)]^{1/2}, \quad (2)$$

where γ is the liquid-gas surface tension, K is the electrical conductivity, and I is the emitted current. Clearly a recirculating flow exists if $U \gtrsim Q/L_c^2$.

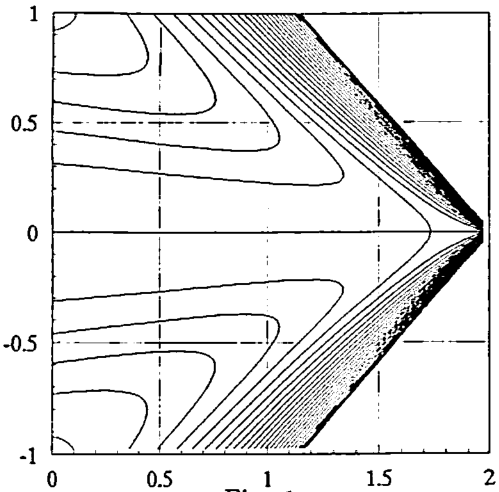

Fig. 1

A characteristic Reynolds number of the flow, defined in the usual form

$$Re = UL_c/\nu = [(\gamma\epsilon_o\rho^2 I^2)/(L_c K^2\mu^4)]^{1/2},$$

(ρ and ν are the density and kinematic viscosity respectively) permits to distinguish two different hydrodynamic regimes: $Re \ll 1$, which corresponds to the case of very viscous and highly conducting liquids and $Re \gg 1$ for liquids with sufficiently small electrical conductivity and viscosity.
In the limit $Re \ll 1$ (creeping flow), the flow driven by the shear stress given in (1) can be represented by a stream function of the form

$$\Psi = r^{1/2}f(x), \quad x = \cos\theta, \quad \cos\alpha \leq x \leq 1, \quad (3)$$

with f satisfying the following equation and boundary conditions

$$(1-x^2)^2 f'''' - 4x(1-x^2)f''' + (3/2)(1-x^2)f'' - 15f/16 = 0,$$

$$f(1) = 0, \quad f(\cos\alpha) = 0, \quad f''(\cos\alpha) = -\Gamma/\mu, \quad f'(1) \neq \infty.$$

Streamlines corresponding to this flow plus a pure sink at the cone's apex are plotted in Fig. 1.

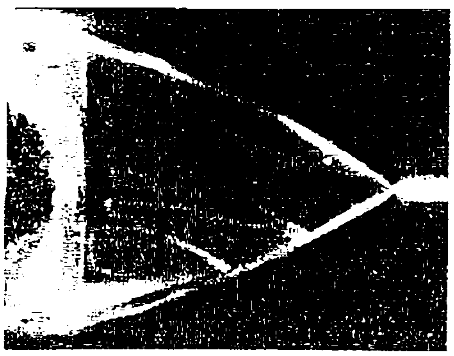

Fig. 2

Fernández Feria et al. (1995) have considered the boundary layer aproximation of a class of conically flows produced by a radial shear stress of the form (1) acting on the cone surface. This flow can be useful for modelling the flow inside Taylor cones. The flow structure found consists of a viscous boundary layer at the cone surface, which transmit the shear and sets the core of the cone into an inviscid conical motion composed by a recirculating meridional motion plus a swirl such as it can be seen in Fig. 2. The inviscid motion is singular at the axis but may be regularized through ahother viscous boundary layer.

The analysis yields the surface velocity as a function of the tangential stress and other quantities, of interest in electrosprays, which can be tested in future experimental measurements.

REFERENCES

[1] Bailey, A.G. 1994. *Electrostatic Spraying in Liquids.* John Wiley, New York.

[2] Fenn, J.B., Mann, M., Meng, C.K., Wong, C.F., and Whitehouse, C. 1989. Electrospray ionization for mass spectrometry of large biomolecules. *Science* **246**, 64-71.

[3] Hayati,I., Bailey, A.I., and Thadros, Th.F. 1986. Mechanism of stable jet formation in electrohydrodynamic atomization. *Nature* **319**, 41-43.

[4] Fernández-Feria, R., Fernánded de la Mora, J., and Barrero, A., 1996. Conically similar swirling flows at high Reynolds numbers. Part I. One cell solutions. Submitted to *J. of Fluid Mech.*

[5] Shtern, V. and Barrero, A. 1994. Striking features of fluid flows in Taylor cones related to electrosprays. *J Aerosol Sci.* **25**, 1049-1063.

[6] Shtern, V. and Barrero, A. 1995a. Bifurcation of swirl in liquid cones. *J. Fluid Mech.* **300**, 169-205.

[7] Shtern, V. and Barrero, A. 1995b. Instability nature of the swirl appearance in liquid cones. *Phys. Rev. E.* **52**, 627-635.