A HYDRODYNAMICAL STUDY OF THE INSTABILITY OF A PLANAR LIQUID METAL ION SOURCE (SUMMARY)

N. Miskovsky, J. He, P. Cutler, M. Chung

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A HYDRODYNAMICAL STUDY OF THE INSTABILITY OF A PLANAR LIQUID METAL ION SOURCE[1] (SUMMARY)

N.M. MISKOVSKY, J.HE, P.H. CUTLER and M. CHUNG[2]

Department of Physics, The Pennsylvania State University, University Park, PA 16802, U.S.A.

Liquid metal ion sources (LMIS) are of interest in diverse areas of technology since they provide a high brightness, quasi-point source of ions for high resolution ion beam lithography, microfabrication, surface analysis and other potential applications[1]. The technical difficulties of building and operating stable sources have been largely overcome. The basic physics of source operation and ion formation is, however, still incompletely understood. Krohn and Ringo first described the fundamental processes of ion emission from liquid metal tips in a strong electric field[2]. Subsequently, Gomer[3] and others[4-8] analyzed the mechanism of LMIS and developed theoretical models to explain the shape and size of the ion emitting region.

The electrohydrodynamical effect, that is, the onset of instability and breakdown, which appears for a critical voltage applied on the tips was first studied by Zeleny[9] and Taylor[10]. Recently, Chung et. al.[7] made an analytical and numerical study of the equilibrium shape and stability of an electrically stressed fluid with an axially symmetric arbitrary shaped surface in the quasi-electrohydrostatic limit. They did a stability analysis required for physically acceptable shapes using a general mechanical criterion applied earlier by Zeleny[9] in his analysis of the stability of charged droplets. Chung, et. al.[7,8] used their results to argue that Taylor had not utilized any proper stability criterion. Furthermore, it was demonstrated by them that, in fact, Taylor used only an equilibrium condition for the establishment of a "rigid" infinite cone in the hydrostatic limit. Explicity, Chung, et. al. have shown that it is not possible to physically form a liquid (i.e., deformable) structure with a Taylor or any other conical configuration by the application of an increasing electric field under quasi-hydrostatic conditions. When a proper stability analysis is made, it is found that the Taylor cone is not a stable equilibrium shape in either the hydrostatic or hydrodynamic limit[8]. This has been confirmed by Zheng and Linsu from a numerical solution of the Navier-Stokes equation[11], and also discussed by Gabovich[4].

Miskovsky et. al.[12] subsequently developed an electrohydrodynamic capillary wave theory for ion and droplet emission in electrically stressed conducting viscous fluids based on a mathematical fromalism introduced by Melcher, et. al.[13,14] and Grossmann et. al.[15]. As the simplest analytical application of this theory we have chosen a model consisting of a planar fluid surface supported on a rigid electrode a distance 'a' below the unperturbed surface. A parallel planar counterelectrode is at a distance 'b' from the unperturbed surface. The same model was recently used by Pregenzer[16], to study high power liquid metal ion diodes for inertial confinement fusion experiments at Sandia National Laboratories. She included graviational effects, but neglected the viscosity of the fluid. In our study, we apply the electrohydrodynamic capillary wave theory to a planar model of a LMIS, which also includes viscosity. Instead of the Bernoulli equation, as used by Pregenzer, we have solved the Navier-Stokes equation subject to a time-dependment Laplace-Young stress boundary condition, which now includes the frictional tensor. The effects of surface tension, viscosity and gravity on the critical electric field were analyzed. Although it was found that the surface tension dominates both gravity and viscosity in determining the critical electric field for breakdown, viscous effects are important, and significantly so for the higher mass liquid metals.

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(2) Department of Physics, University of Ulsan, Kyungman, Korea

In our analysis, we assume that the distubance from equilibrium is harmonic and given by $\xi = \mathrm{Re}\hat{\xi}\exp(st + ikx)$. The disperion relation can be shown to be[17]:

$$\frac{\rho^2}{k^2}\nu^2q^4\coth ka - 2\nu^2\rho^2q^2\coth ka + 4\nu^2kq\coth ka + \left[\rho\varepsilon_oE_o{}^2\coth kb - \frac{\rho g+\gamma k^2}{k} - \nu^2\rho^2k^2\coth ka\right]=0$$

where x is the coordinate parallel to the unperturbed surface and $q^2 = k^2 + s/\nu$, with k the wave number, γ the surface tension, E_o the average electric field, ρ the density, and ν the dynamic viscosity. If s is purely real and greater than zero, the phase velocity of the wave is zero and the amplitude of the disturbance increases without bound, leading to a growing instability.

The results of the calculation can be summarized as follows for the case in which the electric field was fixed at a value to yield a dominant wavelength, i.e., the wavelength corresponding to the maximum growth rate of 0.8mm:

1a. The effect of viscosity on the growth rate varies from about 1% for Li to 8% for Au.
1b. The effect of viscosity on the wavelenth of the dominant mode ranges from ~ 0% in Li to 10% for Au.
1c. Of those liquid metals examined (Li, Al, Sn, Au), the most unstable is Li. This is directly related to the fact that the surface tension is the dominant factor and is smallest for Li.

When the electric field was varied from 1×10^7 to 2×10^9 V/m it was found that:

2a. Viscosity has a significant effect on the growth time and increases with electric field. For Au the variation is ~ 2% to about 40% at the highest field.
2b. The effect of viscosity on the dominant wavelength for Au varies from about 4% to 38%
2c. The gravitational field has a negligible effect on the growth time (less than 1%) for all field values.
2d. The gravitational field produces only a maximum change of 5% in the dominant wavelength for all fields.

Within this model the <u>local</u> electric field is given by the following expression:

$$E=\left[E_o{}^2 + \frac{2k\xi E_o{}^2}{\mathrm{Sinh}\ kb}\cosh k(\xi-b) + \left(\frac{k\xi E_o}{\sinh kb}\right)^2\right]^{\frac{1}{2}} \approx E_o\left[1 + \frac{k\xi}{\sinh kb}\cosh k(\xi-b)\right] ,$$

where z is the coordinate normal to the unperturbed liquid surface. Near the perturbed liquid protrusion the electric field is found to be about six times larger than the electric field averaged over the same liquid surface.

In summary, we have investigated the effect of viscosity and gravity on the spectrum of unstable wavelengths for a LMIS within the planar surface capillary wave model. Using the complete set of hydrodynamical equations we have derived the dispersion relation for surface waves and calculated the dominant wavelength and the growth rate as a function of field. In addition, it was found that viscosity plays a significant role in determining the growth rate and the dominant mode. This suggests that viscosity should be included in the investigations of the instabilities in LMIS and in any physically reasonable model of an EHD source. Finally, it was found that the local electric field is much larger than the average field of the perturbed fluid surface, implying that non-linear effects can be important.

References

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1. J. Melngailis, J. Vac. Sci. Technol. <u>B5</u>, 469 (1987).
2. V. E. Krohn and R. Ringo, Appl. Phys. Lett. <u>27</u>, 479 (1979).
3. R. Gomer, Appl. Phys. <u>19</u>, 365 (1979).
4. M. D. Gabovich, Sov. Phys. Usp. <u>26</u> (5), 447 (1983).
5. D. R. Kingham and L.W. Swanson, Appl. Phys. <u>A34</u>, 123 (1984).
6. C. Bartoli, H. von Rhoden, S. P. Thompson and J. Bollmens, J. de Phys. <u>D17</u>, 2473 (1984).
7. M. Chung, N. M. Miskovsky, P. H. Cutler, T. E. Feuchtwang and E. Kazes, J. Vac. Sci. Technol. <u>B5</u>, 1628 (1987).
8. M. Chung, P. H. Cutler, T. E. Feuchtwang, E. Kazes and N. M. Miskovsky, J. de Phys. <u>C7</u>, 351 (1986).
9. J. Zeleny, Proc. Cambridge Phil. Soc. <u>18</u>, 71 (1915); Phys. Rev. <u>10</u>, 1 (1917).
10. G. I. Taylor, Proc. Roy. Soc. (London) <u>A280</u>, 383 (1964).
11. Cui Zheng and Tong Linsu, J. Vac. Sci. Technol. <u>B6</u>, 2104 (1988).
12. N. M. Miskovsky, M. Chung, P. H. Cutler, T. E. Feuchtwang and E. Kazes, J. Vac. Sci. Technol. <u>A6</u>, 2992(1988).

13. J. R. Melcher, Field-coupled Surface Waves (MIT Press, Cambridge, MA, 1963).
14. J. R. Melcher and C. V. Smith, Phys. of Fluids 12, 778 (1969).
15. S. Grossmann and A. Muller, Z. Phys. B57, 161 (1984).
16. A. L. Pregenzer, J. Appl. Phys. 58, 4509 (1985).
17. The details of the derivation are to be published elsewhere.