The physics of Electrospray, Flow Focusing and Flow Blurring: a revision of three ultra-fine liquid atomization systems

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Abstract

We propose a revision of the basic underlying physics of three ultra-fine and energy-efficient liquid spraying systems: Electrospray, Flow Focusing and Flow Blurring. While the first two involve capillary cone-jets, natural microfluidic structures arising in steady capillary tip-streaming to yield extremely fine and homogeneously sized sprays, the third results from a remarkably simple modification of an axisymmetric Flow Focusing geometry, leading to a new atomization process with surprising features, as shown by the analysis of the resulting droplet size distributions. We show how intelligent device design and geometrical meso-scale management can be implemented to manage Reynolds and Weber numbers down to the just appropriate ranges where mass productivity and control combine to yield maximum aerosol quality and production efficiency. The immense variety of applications for these technologies is discussed.

First, we analyze steady capillary cone-jets, and the boundaries of the stability region of steady jetting are calculated. We describe these limitations by instability mechanisms associated with the local flow structure in the tip and the issuing jet, and with the global behaviour of the meniscus. Second, to undertake a general physical treatment of cone-jets in steady regime, we analyze the energy balance at the tips of both flow focusing and electrospray. This analysis yields a fundamental result: if the electrospray data are expressed in terms of an effective pressure drop, both phenomena satisfy the same scaling law for the droplet size, which exhibits nearly complete similarity in the parameter window where quasi monodisperse sprays are produced. The effective pressure drop is a function of the liquid properties exclusively, i.e., it does not depend on the operational parameters (flow rate and applied voltage). Moreover, the stability limits of the operational regimes are analyzed in detail, and shown to display fundamental coincidences between flow focusing and electrospray as well. In addition, the role of the elongational viscous stresses is also incorporated, showing that, when properly scaled, the systems exhibit the same kind of asymptotic tendencies for large and small Reynolds of other classical flows. These results provide a most useful general description and predictive scaling laws for (i) nearly monodisperse micro/nano-spraying based on steady cone-jets, and (ii) polydisperse, efficient ultra-fine spraying.

Key words: Flow Focusing, Electrospray, Flow Blurring, Ultra-fine liquid atomization