Journal of Electrostatics 72 (2014) 330–335

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Electrohydrodynamic cone-jet bridges: Stability diagram and operating modes

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ARTICLE INFO

Article history:
Received 4 January 2014
Received in revised form
5 May 2014
Accepted 29 May 2014
Available online 12 June 2014

Keywords:
Electrohydrodynamics
Taylor cone-jet
Liquid bridge
Stability diagram
Operating modes
Capillary breakup

ABSTRACT

An electrohydrodynamic cone-jet bridge is formed when two opposing Taylor cones are bridged by a liquid jet. We used high-speed video imaging to systematically investigate the operating regimes of the cone-jet bridge established between a nozzle and a liquid pool that were closely separated. There was a stability island for the cone-jet bridge in the voltage-flow rate operating diagram, and the stable bridge could only be formed above a minimum flow rate and at an intermediate range of voltages. In the vicinity of the stability island, the cone-jet bridge broke up via a thinning or beading mode.

1. Introduction

An electrohydrodynamic cone-jet bridge is formed when two closely separated Taylor cones [1] are connected by a liquid column [2]. The bridging column evolves from the thin jet emitted from a single cone, i.e. the conventional Taylor cone-jet [3–7]. However, the close presence of the counter cone fundamentally alters the properties of the electrohydrodynamic jet, e.g. the bridging jet is typically dominated by Ohmic current and much larger in diameter compared to the conventional jet [2]. The cone-jet bridge is related to other forms of electrohydrodynamic liquid bridges [8–16], but its morphology is distinct with two opposing cones bridged by a slender jet. Although a non-electrical liquid bridge is unstable when the length of the static bridge exceeds its circumference [17–20], electrohydrodynamic bridges can be stabilized by radial polarization stresses to achieve a much larger aspect ratio [2,8,21–27].

For the conventional cone-jet, voltage (V) and flow rate (Q) are the main external control variables, and the V–Q operating diagram is an indispensable guide for accessing the various modes of stable and unstable cone-jets [5,7,28–35]. For a given working fluid with a fixed electrode separation, a minimum flow rate is needed to sustain a steady jet. Above the minimum flow rate, a steady cone-jet can be maintained for an intermediate range of voltages. The upper and lower voltage boundaries merge at the minimum flow rate, giving rise to a stability island on the V–Q map [5,7].

The main objective of this paper is to establish the V–Q operating diagram and identify the operating modes of the cone-jet bridges. In addition to reporting the bridge morphologies within the stability island as a function of voltage and flow rate, we also briefly discuss the thinning/beading breakup modes [36–38] near the lower/upper stability boundaries.

2. Experimental setup

We adopted a nozzle-to-pool configuration to study the cone-jet bridge (Fig. 1). A tapered glass nozzle (New Objective TT360-150-50-N-5) with a length of 20 mm and an inner/outer diameter of 140/200 μm at the nozzle exit was grounded with respect to a liquid pool, which was negatively electrified with a high-voltage source (Trek 610E). The glass nozzle was above the center of the liquid pool and perpendicular to it. The non-conducting nozzle was affixed to a tubing sleeve and attached to a metallic union for hydraulic and electrical connections; see Fig. 1a of Ref. [39] for a detailed schematic. The liquid pool was prepared by filling the working fluid in a rectangular container with a bottom wall made of aluminum (15 mm × 15 mm) and four glass walls on the side with a height of 6 mm. A circular hole of 1 mm diameter was drilled at the center of the bottom plate for active liquid drainage. Ethylene glycol (CAS No. 107-21-1) was used as the working fluid with the conductivity doped to

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http://dx.doi.org/10.1016/j.elstat.2014.05.004
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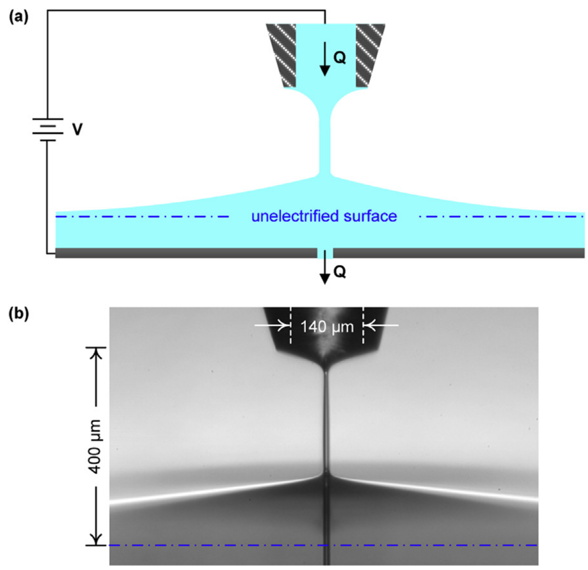

Fig. 1. (a) Schematic (not to scale) of cone-jet bridge formation between a nozzle and a liquid pool. The glass nozzle was electrified via a metallic union at a voltage V with respect to the liquid pool, and the working fluid was supplied and extracted at the same flow rate Q to maintain a constant liquid volume. The dot-dashed line indicated the position of the pool surface prior to electrification. (b) A sample cone-jet bridge of 10 μS/cm ethylene glycol at 2 kV and 300 μL/h, where the bridge was pinned on the outer rim of the nozzle. With respect to the undeformed pool surface, the nozzle-to-pool separation was maintained at 400 μm unless otherwise noted. Note that the the tapered glass nozzle had an inner/outer diameter of 140/200 μm at the exit, and the conical base on the nozzle could span the inner or outer rim depending on the operating conditions.

10 μS/cm by sodium borate, and ambient air was the surrounding dielectric medium. The working fluid was infused and withdrawn at the same flow rate with two dual-mode syringe pumps (Legato 180). The separation between the nozzle exit and the surface of the undeformed liquid pool was fixed at 400 μm unless otherwise noted, with care taken to account for the slight liquid overflow (to facilitate imaging) due to pinning at the glass sidewalls. The resulting cone-jet bridge was monitored by a high-speed camera (Phantom V710) via a long-distance microscope (Infinity K2 with a 4× objective), which was tilted 5° unless otherwise noted.

Our setup deviated from the initial report where the cone-jet bridge was horizontally oriented, and the counter cone was attached to a textured substrate vertically orientated for gravitational drainage [2]. In Fig. 1, the bridge was orientated vertically to eliminate gravitationally induced asymmetry particularly on each Taylor cone. The bridge volume was held constant by extracting from the pool at the same flow rate as that supplied to the nozzle. The active drainage of the working fluid was incorporated to avoid complications arising from a potential mismatch in the feeding and draining rates.

3. Results and discussions

We now discuss the conditions for stable cone-jet bridges by establishing a V–Q stability diagram and documenting the operating modes with respect to this diagram. We used 10 μS/cm ethylene glycol as a model working fluid, although many other working fluids used in conventional electrospraying are also conducive to cone-jet bridges [2].

3.1. Formation process

As discussed in the original report [2], close electrode separation is crucial to the formation of the cone-jet bridge which evolves from a single cone-jet. We established the cone-jet bridge with the liquid pool, which was closely positioned from the nozzle (Fig. 1). Although the liquid pool replaced the textured substrate used in Ref. [2] as the counter electrode, the cone-jet bridge formation process was very similar.

The representative formation process in Fig. 2 could be divided into three steps: (i) when electrified, an upstream cone-jet [3,5] was issued from the nozzle while an inverse Taylor cone [1] developed from the liquid pool. (ii) When the inverse cone approached the upstream cone at a close enough separation, a second jet was issued from the inverse cone, and the two opposing cones bridged together after the two jets merged. Note that the development of the counter jet was much clearer in Fig. 2 of Ref. [2], where the two opposing cones were slightly off-centered as a result of the asymmetry due to gravitational drainage. (iii) The cone-jet bridge relaxed to a steady configuration with two receded Taylor cones connected by a slender liquid column. The actively drained liquid pool offered not only a deformable interface leading to the inverse cone, but also a mechanism to maintain a constant volume for the steady cone-jet bridge.

3.2. Operating diagram

To obtain the operating diagram for steady cone-jet bridges ("stable bridge" in Fig. 3), the flow rate was consistently reduced from 400 μL/h at 50 μL/h decrements. At each flow rate, the voltage was consistently increased from low to high to identify the lower and upper voltage boundaries, between which a steady cone-jet bridge could be formed. The consistent procedure, particularly in the direction of voltage variation, was designed to minimize the hysteresis in the V–Q operating diagram [40,41]. Although the hysteresis in the operating voltage range is known to be significant for single cone-jet [5,7], the hysteresis for the cone-jet bridge was observed to be small, typically within ±0.2 kV for both the lower and upper boundaries.

For comparison, we also constructed the operating diagram for conventional single cone-jet in a similar fashion ("stable jet" in Fig. 3). For this purpose, the setup in Fig. 1 was modified so that the liquid pool was eliminated and the nozzle exit was 400 μm apart from the top surface of the holed aluminum plate. With such a close

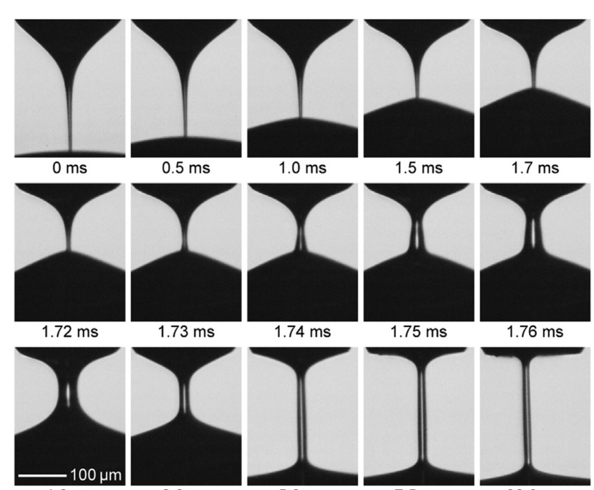

Fig. 2. Formation process of the cone-jet bridge at 3.5 kV and 300 μL/h. Top row: emergence of the counter cone from the liquid pool; middle row: merging of the counter cone-jet with the upstream Taylor cone-jet issued from the nozzle; bottom row: receding of the Taylor cones toward the steady-state configuration of the liquid bridge.