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Absolute and convective instability of a charged viscoelastic liquid jet

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ABSTRACT

The absolute and convective instability of an electrically charged viscoelastic liquid jet is studied. The liquid is assumed to be (i) a dilute polymer solution described by the Oldroyd-B viscoelastic model, and also and (ii) a leaky dielectric defined by the Taylor–Melcher leaky dielectric theory. A generalized eigenvalue equation is obtained and solved numerically. Two different viscoelastic liquids, i.e. a PEO aqueous solution and a PIB Boger fluid, are taken as examples to study the effect of electric field and elasticity on the absolute and convective instability characteristic of the axisymmetric and first non-axisymmetric modes of a viscoelastic jet. The analysis shows that normal electric field may induce absolute instability of both axisymmetric and non-axisymmetric modes, being the effect of electric field larger on the latter. Elasticity has a profound destabilizing effect on the absolute and convective instability of the axisymmetric mode while its effect on the non-axisymmetric mode is quite limited. Strategies for suppressing absolute instability of an electrically charged viscoelastic jet are explored. The result indicates that increasing jet velocity or decreasing jet radius may effectively avoid the occurrence of absolute instability.

1. Introduction

In electrospraying and electrospinning, high-molecular polymer solutions are frequently used, see e.g. [1–4] among others. Different from Newtonian liquids, polymer solutions usually exhibit distinct rheological features. Particularly, the viscoelasticity of a polymer may substantially influence the behavior of the issued jet, consequently affecting the morphology of resulting products.

On the other hand, the behavior of a jet in either electrospraying or electrospinning is highly related to its instability characteristics. It is a well known fact that the dominant mode in electrospraying is the varicose mode, where axisymmetric perturbations tend to predominate over other perturbations, as is shown in Fig. 1a, while in electrospinning the dominant mode is the kink mode, i.e. the first non-axisymmetric perturbations are absolutely predominant ones, as is shown in Fig. 1b. These facts simply reflect the different underlying breakup mechanisms behind electrospray and electrospinning: while the object of the former process is to produce a *spray* by electrical forces, and thus breaking the jet into small pieces is essential, the latter aims to stretch a certain material (viscous liquid or polymeric solution) into extremely thin, ideally continuous filaments. In this latter case, the natural way to dramatically increase the jet's length without a drastic overall mass acceleration is to deviate and stretch the jet perpendicularly to the issuing direction, i.e. the kink mode. The force necessary to provoke this stretching perpendicular to the issuing direction of the jet is provided by the strong radial electric field generated by its own enormous surface charge.

To date, a number of researches have devoted their efforts to describe the instability of viscoelastic jets in the presence or absence of electric environments. Among them, Reneker el al. [5] and Yarin et al. [6] established a viscoelastic mode to simulate numerically the highly nonlinear bending instability of a jet in electrospinning. Brenn et al. [7] and Liu and Liu [8,9] studied the axisymmetric and non-axisymmetric instability of a non-Newtonian jet in the absence of electric fields. Carroll and Joo [10,11] studied the linear axisymmetric instability of an electrified viscoelastic jet. Montanero and Gañán-Calvo [12] analyzed the spatiotemporal instability of the axisymmetric mode of an Oldroyd-B viscoelastic liquid jet in a medium of a co-flowing liquid flow. Li et al. [13] performed a linear analysis of the competition between axisymmetric and non-axisymmetric instability of an electrically charged viscoelastic liquid jet. It was found that either the axisymmetric mode or the first non-axisymmetric mode is predominant in jet instability depending on the level of electrification and that elasticity destabilizes both modes, particularly the axisymmetric one. Ruo et al. [14] examined the influence of unrelaxed elastic tension on the three-dimensional temporal instability of a viscoelastic liquid jet. They concluded that in the presence of unrelaxed tension elasticity plays a stabilizing role in the instability of the axisymmetric and

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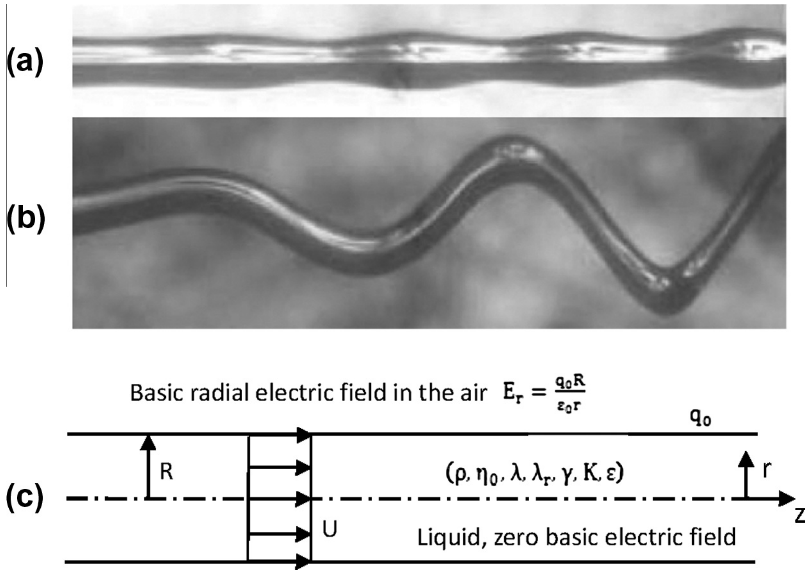

Fig. 1. Photographs of (a) the axisymmetric varicose mode, (b) the non-axisymmetric kink mode, and (c) schematic description of the theoretical model.

non-axisymmetric modes. Later they extended their research to the electric environment [15].

Electric field is the driving factor in electrospraying and electrospinning. First, at the outlet of flow, electric field provides the conditions for the formation of a critically stable meniscus structure, which is called Taylor cone, characterized by the equilibrium between surface tension and the electrostatic force due to the surface charges. In turn, this meniscus provides the sustaining mechanic structure for a singular fluidic phenomenon: from its apex, a stable, extremely thin jet is formed under certain electric potential and flow rate. The diameter of that jet is normally two or three orders smaller than that of the outlet, down to micro-and nano-meters [16–18]. The downstream evolution and breakup of the electrically charged jet yields small drops and ultra-fine fibers. The electric field due to the surface charges promotes the instability of jet, enhancing its breakup into droplets or its violent stretching by a whipping movement [13,19]. Besides, the electric charges induced by the electric field in the droplets and fibers normally prevent their coalescence before solidification takes place [20].

The present work is motivated by the fact that in electrospraying and electrospinning the stable cone-jet structure is only formed under a certain range of applied electric fields and flow rates. Beyond this range the jet may become globally unstable, which may provoke catastrophic situations in continuous production [21–23]. Therefore it is of importance to study the global instability of the jet. Here, the absolute-convective instability transition provided by a spatiotemporal analysis is the first step to understand the global instability phenomenon [24–29]. Absolute and convective instability was soon identified as a fundamental concept in instability analysis. In fact, while convective instabilities leave the system locally unaffected (they are "flushed" by the basic flow), absolute instabilities grow without limitation at the point where they appear, leading to a global catastrophe of the system. In practical terms, for a flow released from a capillary, if a jet is formed and becomes unstable at some distance downstream, it is regarded to be convectively unstable, but if no jet is formed and instability happens near the exit of capillary, the hypothetical jet structure is regarded to be absolutely unstable [30].

The absolute and convective instability of jet has been studied extensively. Taking an axisymmetric model of a charged Newtonian liquid jet, López-Herrera et al. [24] calculated the critical Weber number at the boundary of absolute and convective instability and found that the electric force has a secondary role in the absolute to convective instability transition of jet. Extending their research to three-dimensional scope, Li et al. [25] studied systematically the linear spatiotemporal instability of a viscous jet of low permittivity, low conductivity liquid under both radial and axial electric fields. The absolute and convective instability transition was explored in the four-parameter space (the Weber number, the Reynolds number, the electrical Bond number and the tangential electric field) for both the axisymmetric and first non-axisymmetric modes. Taking flow focusing as application background, Herrada et al. [26] studied the jetting-dripping transition of a compound capillary jet. They calculated the critical Weber number as a function of the radius ratio for the axisymmetric case. Vega et al. [27] studied experimentally and numerically the influence of the flow rate, the distance between the capillary meniscus and the orifice, as well as liquid properties on the status of flow. Three different regimes, i.e. the steady jetting regime, the local instability regime and the global instability regime, were identified. Montanero et al. [28] and Acero et al. [29] performed an experimental study on the global instability of a viscous liquid jet focused by a coaxial jet stream, considering different geometric configurations of the experimental apparatus utilized to generate the jet. Si et al. [31] explored the modes in flow focusing, among which the axisymmetric jetting mode was considered to be convectively unstable and the dripping mode to be absolutely unstable. Clasen et al. [32] investigated the jetting-dripping transition of a dilute polymer solution jet.

In this paper we investigate the absolute and convective instability of an electrified viscoelastic liquid jet. It is organized as follows. In Section 2 the theoretical model is established and the formulation is presented. The governing equations and boundary conditions are transformed into a generalized eigenvalue problem and the numerical method utilized to solve the problem is briefly stated. In Section 3 the absolute and convective instability characteristic of the axisymmetric and first non-axisymmetric modes of the selected liquid jets are explored. The effects of normal electric field and elasticity on the absolute and convective instability of the unstable modes are studied. In addition, strategies for suppressing absolute instability of a viscoelastic jet are discussed. In Section 4 main conclusion is drawn.

As a general consideration, this work aims to provide additional theoretical basis for the adequate physical description of