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Absolute and convective instability of a coaxial viscous liquid jet under both axial and radial electric fields

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ABSTRACT

The absolute and convective instability of a coaxial viscous liquid jet in both radial and axial electric fields is studied. The outer liquid is assumed to be conducting and to be the driving liquid. The governing equations are solved numerically as a generalized eigenvalue problem. The effects of the parameters on the instability of the axisymmetric para-sinuous and first non-axisymmetric modes are explored. Both the radial and axial electric fields exhibit great effect on the modes. The dominant regions of the modes are identified on distinct parameter planes. The study helps us predict the behaviors of jets in coaxial electrospraying and coaxial electrospinning.

1. Introduction

In the past one or two decades electrically driven liquid jets have been widely applied to industrial engineering. Among them coaxial electrospraying and coaxial electrospinning turn out to be facile and robust methods to fabricate micro/nano capsules, core-sheath nanofibers and hollow nanotubes. Such products have tremendous applications in medical treatments, drug delivery, spraying, encapsulation, emulsions, nanotechnology, biotechnology, polymer industry, optoelectronic devices and so on [1–10].

A few theoretical and experimental studies have been performed on the behaviors and characteristics of the electrified coaxial jet in coaxial electrospraying or coaxial electrospinning. López-Herrera et al. [11] studied experimentally the effect of the flow rates of the inner and outer liquids on the electric current and the size of the compound droplets. In their research the scaling laws were established and compared with those in single-liquid electrospraying. Reznik et al. [12] studied numerically and experimentally the shape of compound droplets at the core–shell exit under the action of a strong electric field. Higuera [13] simulated the shape of a stationary coaxial jet under electric field and the distribution of surface charge and electric stresses along the jet. Hu and Huang [14] studied numerically the flow patterns of two-phase shear-thinning flows in coaxial electrospinning and emphasized the importance of the Weber number. Mei and Chen [15] investigated the effect of surface tension on the particle encapsulation process in coaxial electrospraying experimentally. Li et al. [16,17] studied the temporal instability of the axisymmetric and non-axisymmetric modes of an electrified coaxial jet. So far, the instability in coaxial electrospraying and coaxial electrospinning has not been comprehensively understood yet.

As is well known, jets undergo instability due to capillary. In coaxial electrospraying and coaxial electrospinning, there is something more. The formation of small capsules or thin fibers is closely related to the instability of coaxial jets under the action of electric fields [16,17]. The understanding of the instability behavior of electrified coaxial jets helps predict the characteristic of products.

On the other hand, absolute and convective instability is one important aspect of instability analysis. Take a cylindrical jet as example. When the jet is convectively unstable, all disturbances propagate downstream and the jet has a straight intact length; when the jet is absolutely unstable, disturbances propagate both downstream and upstream and the whole jet is contaminated ultimately. When a jet is perturbed, distinct modes grow simultaneously. The axisymmetric para-sinuous mode turned out to be dominant over all other modes in coaxial electrospraying experiments, where the coaxial jet breaks up into compound droplets at some distance downstream [1,13,16]. Due to the existence of an intact length, the jet is convectively unstable. If the jet is absolutely unstable, it will break up close to the capillary, although compound droplets may be still formed. This is considered to be a non-ideal case, because the absence of a jet section may lead to other problems and influence the quality of droplets. Similarly, in coaxial electrospinning experiments where the first non-axisymmetric mode

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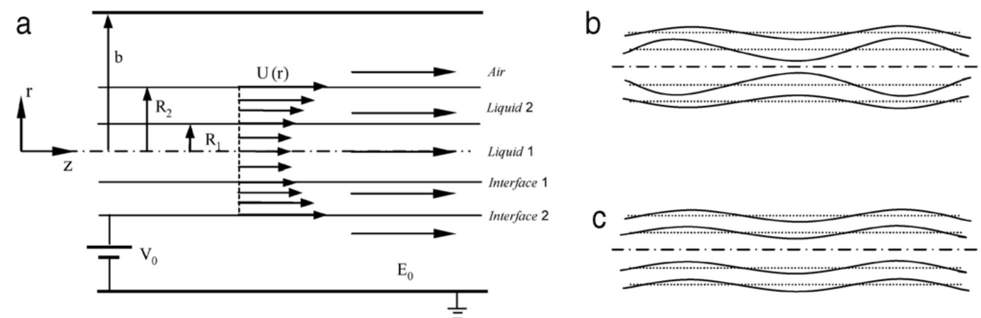

Fig. 1. Schematic description of (a) the theoretical model, (b) the axisymmetric para-sinuous mode and (c) the first non-axisymmetric mode.

is dominant [6,14,16], convective instability permits the existence of a stable straight jet section and disturbances grow not too fast, while in absolute instability state the whole jet is highly unstable.

In the current paper, the absolute and convective instability of a coaxial liquid jet under both radial and axial electric fields is studied. The paper is organized as follows. In Section 2 the theoretical model and the governing equations are given. In Section 3 the numerical results are presented, where the effects of the dimensionless parameters on the absolute and convective instability of the axisymmetric para-sinuous mode and the first non-axisymmetric mode are investigated. Finally the conclusions are drawn in Section 4.

2. Model and equations

The theoretical model in this study is similar to the one considered in [16]. As sketched in Fig. 1, a coaxial cylindrical jet consists of two immiscible, incompressible and viscous liquids. The radius of the inner liquid cylinder is R_1 and the outer radius of the outer liquid layer is R_2. The densities of the inner and outer liquids are ρ_1 and ρ_2, respectively; the dynamic viscosities of the inner and outer liquids are μ_1 and μ_2, respectively. The coaxial jet is surrounded by atmospheric air. The hydrodynamic effect of the air is supposed to be negligible. Two material interfaces exist in the model: the inner interface between the inner and outer liquids and the outer interface between the outer liquid and the air. The interface tension coefficients of the inner and outer interfaces are γ_1 and γ_2, respectively.

The outer liquid, which serves as the driving liquid in coaxial electrospraying and coaxial electrospinning experiments, is usually a leaky dielectric of finite electrical conductivity [16,18]. The effect of finite electrical conductivity of the driving liquid on the instability of the coaxial jet was briefly discussed in [17]. To simplify the problem, in the present model the outer driving liquid is assumed to be a perfect conductor of infinite electrical conductivity. Free charges are relaxed to the interface instantaneously. There is no charge in the liquid bulk. In the numerical simulation of Higuera [13], it was found that the charge density on the inner interface is a small value, about two orders of magnitude smaller than the charge density on the outer interface in the downstream part of the jet. Based on this finding, charge on the inner interface is neglected in the present model. That is, free charge only exists on the outer interface. In such a situation, the inner liquid, which is the driven one, can be a conductor, a leaky dielectric or a dielectric, i.e., its electrical property remains flexible. The ambient air is a perfect dielectric. The effects of magnetic field, temperature and gravitational force are neglected.

The real electric field in electrospraying and electrospinning is rather complicated. Both radial and axial electric field exists, and moreover, the electric field varies along the jet. Nevertheless, in the downstream part of the capillary where the radius of jet varies slowly, the tangential electrical stress is small compared with the normal electrical stress as well as other forces [13]. Therefore, it is reasonable to assume that the axial electric field is a small quantity compared with the radial electric field and the effect of tangential electrical stress on jet radius is negligible. For the convenience of theoretical analysis, a uniform axial electric field of intensity E_0 is assumed to be present in the system. Different from [16] where free charges of a certain density are assumed to accumulate on the outer interface providing a basic radial electric field, in the current model the radial electric field is subjected by imposing a high electric voltage V_0 on the outer interface of the coaxial jet and meanwhile placing a grounded electrode of radius b surrounding the jet. This setting of electric field is more practical. The intensity of radial electric field in the air is $V_0/[r\ln(b/R_2)]$, where r is the radial coordinate.

Suppose the basic flow is steady and axisymmetric. The basic velocity of jet has only one nonzero component in the axial direction. The solution to the basic velocity field is [16]

$$U_1(r) = U_0 + \frac{\varepsilon_3 V_0 E_0}{2\mu_2 R_2^2 \ln(b/R_2)}\left(R_1^2 - R_2^2\right) + \frac{\varepsilon_3 V_0 E_0}{2\mu_1 R_1 R_2 \ln(b/R_2)}\left(r^2 - R_1^2\right), \tag{2.1}$$

$$U_2(r) = U_0 + \frac{\varepsilon_3 V_0 E_0}{2\mu_2 R_2^2 \ln(b/R_2)}\left(r^2 - R_2^2\right), \tag{2.2}$$

where $U(r)$ is the basic axial velocity component, U_0 is the magnitude of velocity at the outer interface, ε is the electrical permittivity and the subscripts 1, 2 and 3 denote the inner liquid, the outer liquid and the air, respectively.

The governing equations of the system are the continuity equation and the Navier–Stokes equation for the flow field, and the Laplace equation for the electric field, i.e.

$$\nabla\cdot\boldsymbol{u}_i = 0, \quad i = 1, 2 \tag{2.3}$$

$$\rho_i\left(\frac{\partial\boldsymbol{u}_i}{\partial t} + \boldsymbol{u}_i\cdot\nabla\boldsymbol{u}_i\right) = -\nabla p_i + \mu_i\nabla^2\boldsymbol{u}_i, \quad i = 1, 2 \tag{2.4}$$

$$\nabla^2 V_i = 0, \quad i = 1, 2, 3 \tag{2.5}$$

where $\boldsymbol{u}$ is the velocity vector, p is the pressure and V is the electrical potential.

The boundary conditions are (1) the kinematic conditions at the perturbed inner and outer interfaces, i.e.

$$u_{ir} = \left(\frac{\partial}{\partial t} + \boldsymbol{u}_i\cdot\nabla\right)\eta_i, \quad i = 1, 2 \tag{2.6}$$

where u_r is the radial component of velocity, η is the deviation of interface away from its original position, and the subscripts 1 and 2 denote the inner and outer interfaces, respectively; (2) the continuity of velocity at the inner interface, i.e.

$$\boldsymbol{u}_1 = \boldsymbol{u}_2; \tag{2.7}$$