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Investigation of electrospun nanofibers with an electrified non-Newtonian jet using differential quadrature method

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ABSTRACT

In this paper, the influence of non-Newtonian rheology of nanofibers on electrospinning process is analyzed numerically. A simple and highly accurate numerical method called the Differential Quadrature Method (DQM), is used for solving the governing equations of electrospinning systems. The validity of the results of DQM solution are verified via comparison with experimental data and a good agreement between the present method and the experimental data is observed. The behavior of the elongation, velocity, stress and total force profiles with variation of some physical parameters are discussed in details. The results show that by increasing the values of yield stress, the fluid elongation is reduced significantly. Furthermore, it is found that Differential Quadrature Method can be easily extended to other strongly nonlinear equations and can be found widely applicable in engineering and science.

Introduction

Electrostatic fiber spinning or 'electrospinning' is a unique process for forming fibers with submicron scale diameters through the action of electrostatic force [1]. The resulting nanofibers are collected as non-woven mats with extremely large surface to mass ratios, which can be used in filtration, catalysis, and biomedical applications [2]. Electrospinning of polymer solutions has gain much attention in the last few years as a cheap and straightforward method to produce nanofibers [3–7]. Electrospinning differs from the traditional wet/dry fiber spinning in a number of ways, of which the most striking differences are the origin of the pulling force and the final fiber diameters. The mechanical pulling forces in the traditional industrial fiber spinning processes lead to fibers in the micrometer range and are contrasted in electrospinning by electrical pulling forces that enable the production of nanofibers [5]. Liu et al. [8] synthesized an alumina (Al_2O_3) nanofibre supported nickel (Ni) catalyst has been successfully

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using electrospinning technique. They characterized Ni/Al_2O_3 catalyst by inductively coupled plasma (ICP), scanning electron microscopy (SEM), N_2 sorption, X-ray diffraction (XRD), high resolution-transmission electron microscopy (HR-TEM), temperature-programmed oxidation (O_2-TPO) and X-ray photoelectron spectroscopy (XPS) measurements. Shahgaldi et al. [9] used the electrospinning method to produce titania-coated (TiO_2) boron nitride nanofibers, Also they studied the effects of heat treatment on the morphology, surface area and hydrogen storage capacity. Wu et al. [10] studied on fabrication of transition/alkaline earth metal oxide composite nanofibers (TAMNs) $Ca_3Co_4O_9$ and $MgCo_3O_5$ as a new class of oxide materials for hydrogen evolution by electrospinning followed by calcinations under mild condition. Also, they characterized it by scanning electron microscopy (SEM), thermogravimetric analysis (TGA), high resolution transmission electron microscope (HR-TEM), Raman spectroscopy, X-ray powder diffraction (XRD) and electrochemical method. Pure and doped ZnO nanofibers with Al and Mg were successfully synthesized via an electrospinning method using a sol–gel containing Polyvinylpyrrolidone as a spinning aid and a zinc nitrate precursor by Yaakob et al. [11]. They concluded that the diameter of the doped nanofibers decreased with increasing viscosity and conductivity, as measured by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Veluru et al. [12] prepared MWCNT-TiO_2 hybrid nanostructures using sol–gel and electrospinning followed by post annealing of as-spun nanofibers at 450 °C per 1 h in air. Most technical problems are inherently nonlinear, these problems and phenomena can be modeled by ordinary or partial nonlinear differential equations to find their behavior in the environment. Mathematical modeling is a vantage point to reach a solution in an engineering problem, so the accurate modeling of nonlinear engineering problems is an important step to obtain accurate solutions. The nonlinear motion of fluid conveying carbon nanotubes was investigated analytically using Euler–Bernoulli and Timoshenko beam theories by Ghasemi et al. [13–15]. Ghoreyshi et al. [16] investigated the antegrade flow effects on flow pulsations in fontan operation numerically. Also, the ultrahigh efficiency gas turbine engine with stator internal combustion and the multistage ultra-high efficiency gas turbine engine were studied numerically [17,18]. Differential quadrature method (DQM) is a numerical technique for solving differential equations which first developed by Bellman et al. [19]. Afterward, that was developed by Shu [20]. The magnetohydrodynamic natural convection boundary-layer flow on a sphere in a porous medium was studied numerically using the differential quadrature method (DQM) by Moghimi et al. [21]. The boundary-layer natural convection flow on a permeable vertical plate with thermal radiation and mass transfer was investigated when the plate moves in its own plane by Talebizadeh et al. [22]. They solved the governing equations by means of an excellent analytical method called homotopy analysis method (HAM) and a higher-order numerical method, namely differential quadrature method (DQM).

The main purpose of this study is to study the influence of non-Newtonian rheology of nanofibers on electrospinning process using DQM. The verification of the DQM results is done by comparison with experimental data. Also, the effects of some physical parameters on elongation, velocity, stress and total force profiles are investigated.

Model description

Consider a rectilinear electrified liquid jet in an electric field parallel to its axis. All variables are assumed to be constant over the radial axis of the jet and change over the Z axis, only. So the flow is considered as one-dimensional model. The fiber is represented by tow charged dimer. Each of dimer possesses a charge e and mass m (see Fig. 1). l is the filament length, h being the distance of the collector plate from the injection point and V_0 the applied voltage.

Let the position of one of the dimer be fixed by non-Coulomb forces. The other dimer is acted by the Coulomb repulsive force $-e^2/l^2$. Also, the force applied to the external field is $-eV_0/h$.

The momentum balance is as following [23]:

$$m\frac{dv}{dt} = -\frac{e^2}{l^2} + \frac{eV_0}{h} + \pi a^2 \sigma \tag{1}$$

where a is the cross-section radius of the bead and v is the velocity of bead which satisfies the kinematics equation:

$$\frac{dl}{dt} = -v \tag{2}$$

The stress σ for a viscoelastic fluid is as follows:

$$\frac{d\sigma}{dt} = -\frac{1}{\tau}(\sigma - \sigma_{HB}) \tag{3}$$

where σ_{HB} and$\tau$are the Herschel–Bulkley stress and time relaxation constant, respectively [24].

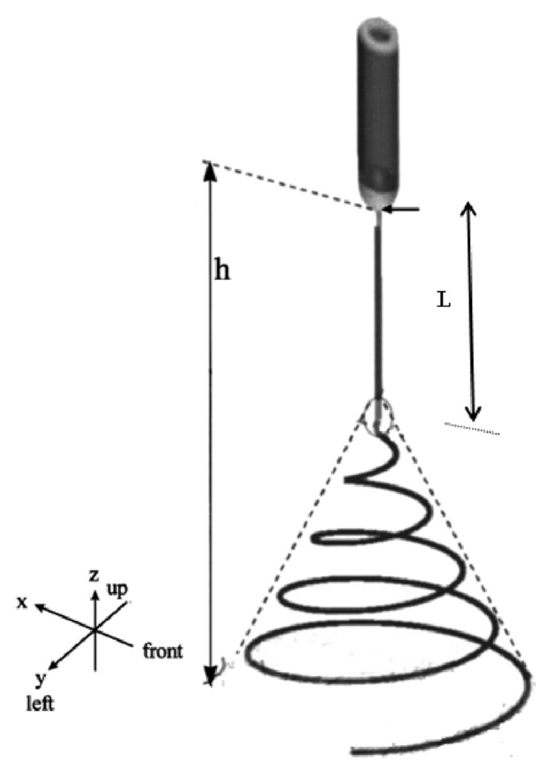

Fig. 1 – Schematic drawing of the electrospinning process.