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Modified electric fields to control the direction of electrospinning jets

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ABSTRACT

Electrospinning is a well known process for fabricating sub-micron size fibers. A high voltage potential is used in electrospinning to launch a polymer jet from a droplet of polymer solution towards a grounded collector. Most of the electrospun fibers collect on the grounded collector, but depending on the design of the electrospinning apparatus and the environment, some of the fibers drift away from the collector and are captured on other objects.

In this work we apply the hypothesis that the electrospinning jet follows the path of the electric field's current density lines. By controlling the direction of the current density lines one can control the path of the electrospinning jet and hence can control the location of where the fibers are collected.

The current density lines are determined by the gradient of the static electric potential field. The electric field is modified in this work by positioning charged electrodes that change the potential field and hence change the potential gradient and the path of the current density lines. In this way, the jet, following the current density lines, can be directed towards desired locations and away from undesired locations. The static electric field was modeled by numerically solving Laplace's equation for the potential field. Electrospinning experiments were conducted with the same geometric arrangement of electrodes for comparison. The results show the center of mass of the electrospinning jets generally followed the current density lines. This work shows it is possible to direct the electrospinning jets away from undesired objects by use of secondary electrodes.

1. Introduction

Electrospinning is a well known process for fabricating micron and submicron sized polymer fibers using an electrostatic field to launch jets from a droplet of polymer solution [1–4]. A simple electrospinning apparatus consists of a high voltage source, a syringe pump to deliver the polymer solution from a syringe to a charged needle, and a grounded collector (Fig. 1). The collector may be a flat surface, a rotating cylindrical drum, or some other shape depending on the application.

The theory behind the electrospinning process is described elsewhere [5]. The high voltage potential applied to the needle charges the droplet of polymer solution and creates electrical forces that exceed the surface tension of the droplet and initiate the launch of the jet. As the jet travels from the needle to the collector it experiences bending instabilities. The bending instabilities cause the jet to stretch and loop onto itself, resulting in jet diameters in the submicron range. The solvent in the polymer solution evaporates from the jet and the jet hardens into a solid fiber. The high voltage is maintained on the polymer drop to sustain the continuous flow of polymer solution to the jet.

During the electrospinning process, electrostatic repulsion between charged ions within the polymer jet causes the loops of the jet to move away from each other while the collective center of mass of the loops of the jet moves towards the grounded collector surface. The time-averaged path of the loops of the jet travels through a three dimensional volume from the needle to the grounded surface that resembles the shape of a right circular cone having its vertex at the needle. The general motion (i.e. center) of this cone follows the local current density lines. The current density lines [6] are analogous to fluid flow streamlines that pass through a unit area of space. The local path of the current density lines are affected by the presence of the charges carried by the jet. We assume in this work is that the path of static electric field current density lines, in the absence of the jet, gives a sufficient approximation to the actual local current density lines for predicting the path of the electrospinning jet.

In most electrospinning applications, objects other than those shown in Fig. 1 are positioned at sufficient distances away that the current density lines towards such objects in the surrounding environment are negligible compared to the current density lines towards the grounded collector. However, in some applications

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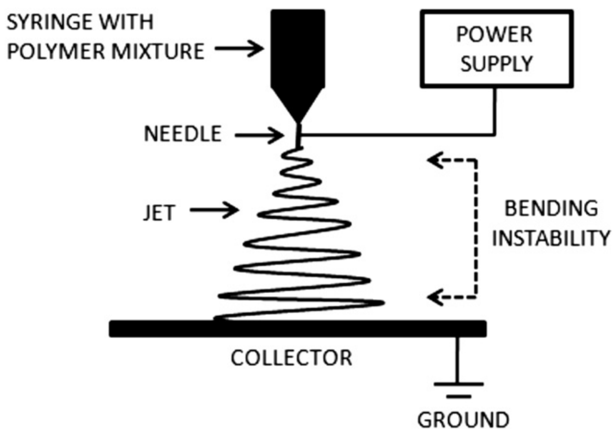

Fig. 1. Schematic diagram of the electrospinning setup.

objects may intrude into the electrospinning space in close enough proximity to attract current density lines from the needle that interfere with the jet movement towards the grounded surface. This latter situation generally results in some fibers collecting on the intruding objects as well as on the grounded collector surface. Examples of these intruding objects are motors used to rotate a collector drum [7] or to rotate devices for collecting nanofiber yarns [8].

In prior studies the electric fields had been modified, such as through the application of secondary electrodes, to control the motion of the electrospinning jet to align the electrospun fibers [9–13]. In other applications, secondary electrodes, such as ring electrodes, were used to aid in the launch and stretching of the jets [14–16].

Control of where the fibers collect is of significant interest when the polymer solution is expensive or may be chemically hazardous. For continuous large scale operations the accumulation of fibers other than on the desired collector may be problematic from an operational perspective. Prediction of the path of the electrospinning jet can greatly enhance the collection efficiency and can be applied for creating specialized fiber mat structures.

In this paper, our objective is to modify the electric field with secondary electrodes to prevent the fibers from collecting in undesired locations. The electric field is modeled with secondary electrodes placed at locations between the needle and the collector to direct the current density lines away from an intruding object such as a motor.

2. Theoretical analysis

Gauss's law, or the conservation of charge [6], models the current density vector, j, for a static electric system in a continuum by setting the gradient of the current density to zero

$$\underline{\nabla}\cdot\underline{j} = 0 \tag{1}$$

The electrical conductivity relates the current density to the potential gradient as

$$\underline{j} = -\sigma\,\underline{\nabla}\,\phi \tag{2}$$

where ϕ is the electric potential (voltage) and σ is the conductivity of the medium.

For a constant conductivity, Eqs. (1) and (2) combine to the form of Laplace's equation in the potential

$$\nabla^2\phi = 0 \tag{3}$$

In rectangular co-ordinates Eq. (3) is

$$\frac{\partial^2\phi}{\partial^2 x}+\frac{\partial^2\phi}{\partial^2 y}+\frac{\partial^2\phi}{\partial^2 z} = 0 \tag{4}$$

The derivatives in Eq. (4) may be approximated by Taylor series expansion over equal positional steps in the three directions

$$h = \Delta x = \Delta y = \Delta z \tag{5}$$

to obtain the equivalent of Eq. (4) in discretized form as [17]

$$\frac{\phi_{i+1jk}-2\phi_{ijk}+\phi_{i-1jk}}{h^2}+\frac{\phi_{ij+1k}-2\phi_{ijk}+\phi_{ij-1k}}{h^2} + \frac{\phi_{ijk+1}-2\phi_{ijk}+\phi_{ijk-1}}{h^2} = 0 \tag{6}$$

This equation simplifies to

$$\phi_{ijk} = \frac{1}{6}\left(\phi_{i+1jk}+\phi_{i-1jk}+\phi_{ij+1k}+\phi_{ij-1k}+\phi_{ijk+1}+\phi_{ijk-1}\right) \tag{7}$$

In a 3-D rectangular grid geometry, Eq. (7) says the potential at the point with indices ijk is equal to the average of the six surrounding grid point potentials, indicated in Fig. 2, and indicated by $i \pm 1, j \pm 1, k \pm 1$ indices.

More efficient numerical schemes for solving Laplace's equation are available. For example, a nine-point difference formula for solving the 2-D Laplace's equation provides $O(h^4)$ accuracy compared to the $O(h^2)$ accuracy of the 2-D form of the Taylor Series expansion in Eq. (6) [18]. However Eq. (6) for the 3-D model gave satisfactory results for this work and the simplicity of the equation made programming easier.

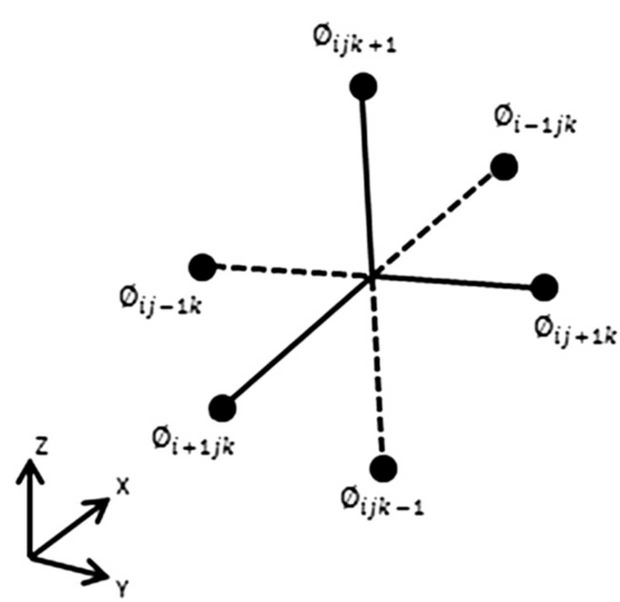

Fig. 2. Notation showing voltage potential at a local point in a rectangular grid and the surrounding points.