Effects of Electric Field on the Multi-jet Electrospinning Process and Fiber Morphology

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Abstract— Single-needle systems have been used in the electrospinning experimental research; but, the low fluid throughput in fiber production has industrial limitations. To meet a high liquid throughput requirement, several multi-jet schemes have been tested in the recent past. The main drawback of these schemes is the deterioration of the local electric field at the needle tip due to the influence of other needles in the arrangement. The aim of the present work is to investigate the electric field distribution in 2-needle arrangements by using finite element analysis. The effects of the orientation of needles on the electric field distribution and hence on the electrospinning process are discussed by using a polyethylene oxide (PEO) solution.

***Index Terms*—Electrospinning, nanofibers, multi-jet, electric field**

I. Introduction

ELECTROSPINNING is a straightforward and inexpensive process that produces continuous nanofibers from submicron diameter down to the nanometer diameter scale through an electrically charged jet of polymer solution consisting of sufficiently long chain molecules that do not break up due to Rayleigh instability. Electrostatic charging of the fluid at the tip of the droplet results in the formation of a well known Taylor cone and when it is subjected to a strong electric field with an appropriate field gradient, the droplet becomes unstable, and a single fluid jet is drawn out from the tip of the Taylor cone. Once the jet flows away from the Taylor cone in nearly a straight line, the traveling liquid jet is subjected to a variety of forces thus the onset of bending instability can be observed, and the electrospun jet takes a complex path and other changes in the shape occur. Meanwhile the electrical forces stretch and thin the jet by very large ratios, and finally the solvent is evaporated and nanofibers are collected on the target.

Even though many researchers have used single-needle systems for electrospinning, the low fluid throughput in spinning has limited the industrial use of single-needle systems. To meet high liquid throughput requirements, several multi-jet schemes have been tested in the recent past [1-3]. The main drawback of these schemes is the deterioration of the local electric field at the needle tip due to the presence of other needles in the arrangement. The aim of the present work is to investigate the electric field distortion in the multiple needle schemes by using finite element analysis and to find its effects on electrospinning process. A polyethylene oxide (PEO) solution was used to conduct the experiments because of its easiness with electrospinning. Furthermore, the fiber diameter and the fiber uniformity are investigated by using scanning electron microscopy (SEM) for different needle to needle spacing.

II. Simulation Work

The electrospinning process highly depends on the electric field, in particular, the local field at the needle; hence, the electrospinning process and the collected fibers. A finite element method based software package, COMSOL® Multiphysics was used for electrostatic field calculations to obtain the results with multi-jet arrangement.

Figure 1 illustrates the COMSOL model that was used to calculate the electric field distribution between the needles and the target. Needles of AWG with 19 inner diameter were used in the modeling and the needles were placed 250mm vertically above the target during the simulation. Figure 2 shows the electric field and potential distribution between the needle/s and the target with the application of 15kV for both single-needle and 2-needle arrangements. The surface plots show the potential distribution; whereas, the arrows illustrates the field distribution. Even though the overall field distribution appears to be same for both cases, the local electric field distribution is significantly different. The maximum electric field strength at the tip is 2.40kV/mm in the case of singe needle arrangement, and 1.74kV/mm for 2-needle arrangement at 15kV respectively. It can be seen that the maximum electric field at the tip of the needle has been significantly weakened in the case of 2- needle arrangement due to the repulsion of field lines.

Figure 3 shows the local electric field distribution at the needle tip for two cases. In the case of single-needle arrangement, a significant enhancement in the electric field is observed at the tip. However in the case of 2-needle arrangement, the local electric field at each needle tip has been deteriorated. Although an identical voltage with similar magnitude and polarity has been applied in both cases, the electric field lines at the tip of the needles in case of 2-needle arrangement is more than one order lower compared to single-needle arrangement due to the repulsive field which has resulted in field distortion at the needle tips.

The spacing between the two needles was varied from 10mm to 100mm in 10mm steps and the simulated field results are shown in Fig.4. As it is shown in Fig.4, the

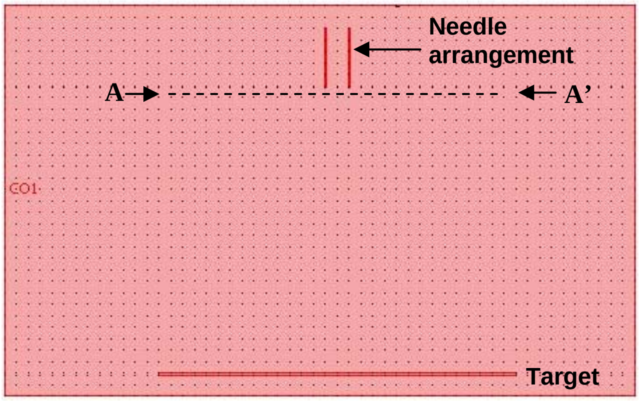

Fig.1. Needle - target arrangement used for FEM simulation.

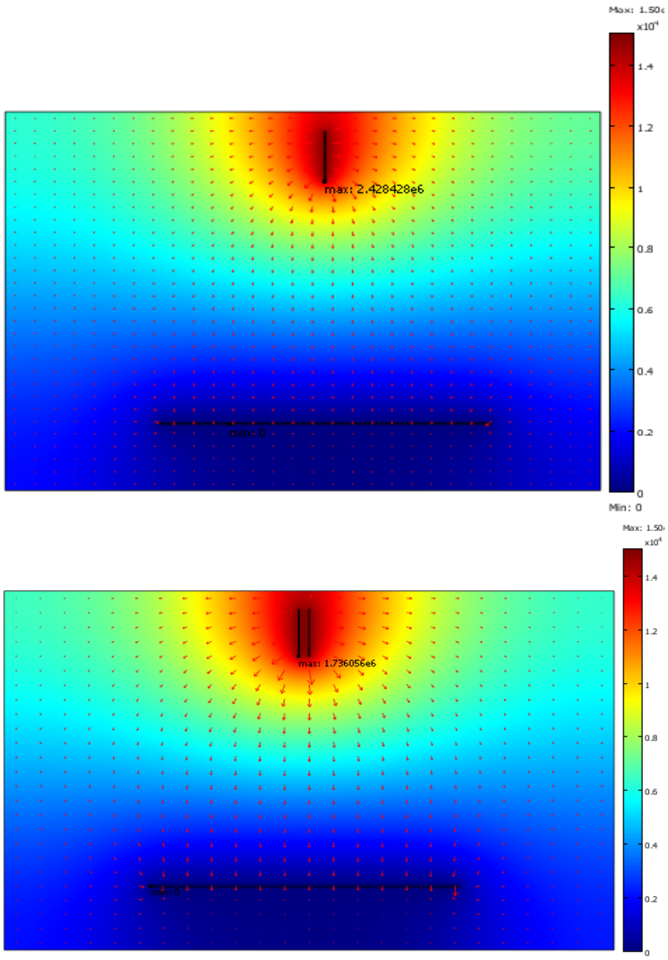

Fig.2. The electric field distribution (a) Single-needle arrangement (b) 2-Needle arrangement.

maximum electric strength can be observed with a single-needle arrangement and then with the 2-needle arrangement for 10mm gap distance. Although the maximum electric field dropped by an order of magnitude with 2-needles, the field varies very little as a function of needle spacing for the range used in this study (10mm to 100mm), without following any specific trend. The reason for this wavering behavior is the change in the distance between the collector edges and the needles as the spacing is changed. Therefore the behavior of the electrospun jet is highly unpredictable for different needle spacing. In addition, it is difficult to achieve fiber uniformity. Most importantly the minimum required voltage to begin the electrospinning process is higher in the case of 2-needle arrangement compared to the single-needle arrangement. Experimental studies were undertaken to correlate the field distortion with the fiber production.

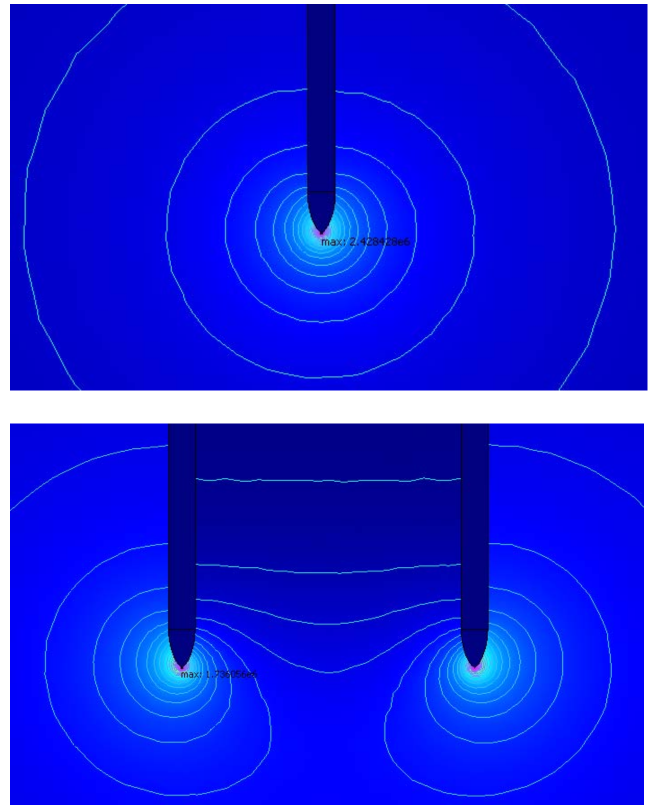

Fig.3. The local electric field distribution (a) Single-needle arrangement (b) 2-Needle arrangement.

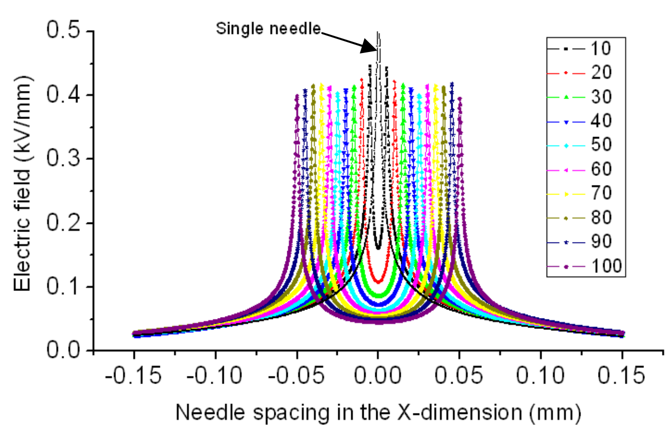

Fig.4. Illustration of the electric field distribution along the line A-A' (Fig. 1) for different needle spacings.

III. Experimental

A. Material preparation

Polyethylene oxide (PEO) with an average molecular weight of 600,000 purchased from Aldrich® was chosen to prepare the solutions. PEO fibers were electrospun using 5% (w/w) concentrations of PEO in de-ionized water. All solutions were stored at room temperature and all electrospinning experiments were done at room temperature and atmospheric air.

B. Experimental Setup

Figure 5 illustrates the experimental setup that was used to perform multi-jet electrospinning experiments. Polymer solution is forced through a syringe needle arrangement at a constant rate of 0.1ml/min from a syringe pump through AWG of 19 inner diameter polyethylene (LDPE) tubes, resulting in formation of a drop of polymer solution at the needle tip. Spellman high voltage DC power supply was used to apply the high voltage between the needles and the collector plate.

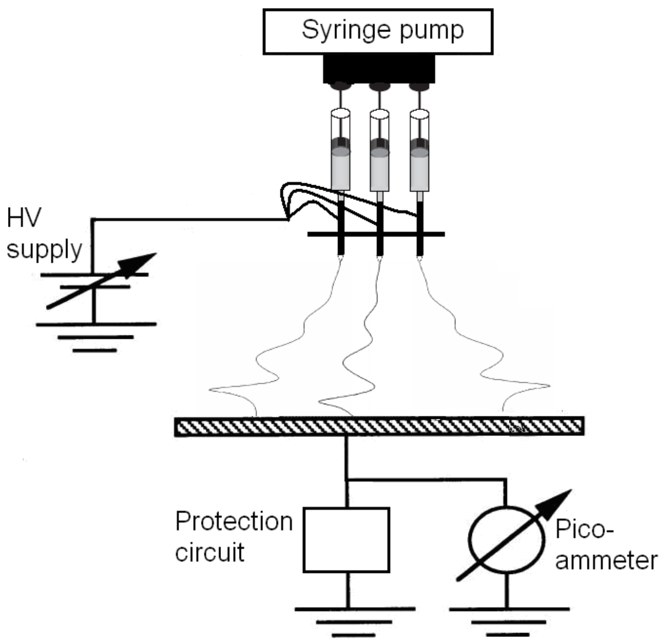

Fig.5. A schematic of the experimental setup used in the multi-jet electrospinning process.

Needles were mounted vertically above the collector plate in all the experiments. Keithley system electrometer (pico-ammeter) model 6514 was used to measure the total jet current and it is connected between the collector plate and the ground electrode with a protection circuit as shown in Fig.5. A voltage of 15kV is applied between the needles and the target and a distance of 250mm was maintained between the needles and the target in all cases. The electrospun fibers were collected on a flat 300mm diameter target. SONY® DCR-HC28 camcorder was used to capture the image of the straight jet portion of the jet during electrospinning. The electrospun fibers were analyzed under an SEM, model Leo 1530 Gemini. About 50 different fiber diameters were used from multiple SEM images to calculate the average fiber diameter for the analysis.

IV. Results and Discussion

A. Behavior of the straight jet portion

As discussed in section II, with the distortion in the local electric field at the needle tip due to the presence of the other needle, the electrospun jet moves away form the vertical line, as shown in Fig.6. The angle between the vertical line and the actual electrospun jet is defined as vertical angle of the straight jet portion, θ.

Figure 7 shows the variation of θ with increasing gap distance between the two needles from 10mm to 100mm for different applied voltages. The angle θ although sharply decreases initially, for needle spacing greater than 40mm, the plots show a behavior which matches with the maximum electric field distribution, Fig. 8. In addition a higher vertical angle can be observed with higher voltage. This is obvious since the local electric field distortion increases with increased voltage.

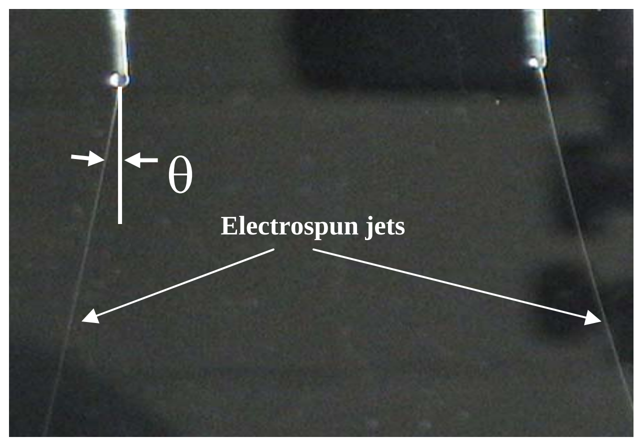

Fig.6. Representation of vertical angle of the straight jet portion of the electrospun jet.

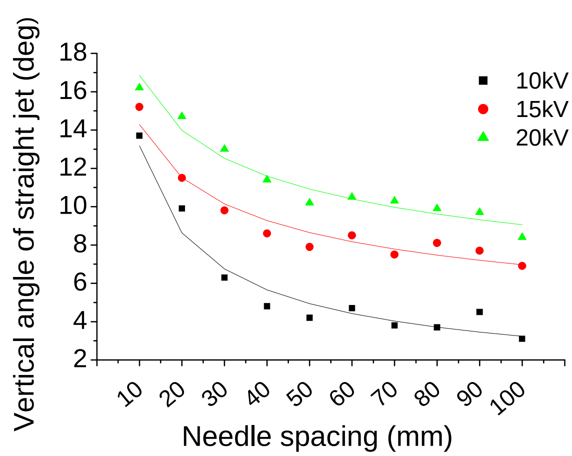

Fig.7. The variation of vertical angle of the straight jet portion for different needle spacings.

B. Behavior of the average jet current

Figure 8 shows the variation of average jet current and calculated maximum electric field strength with the needle spacing. The variation in the average jet current almost follows the variation in the maximum electric field, with the needle spacing. For 2-needle arrangement, the maximum field strength reported is the average of the maximum fields calculated just below the cone tip of two needles. Notably the average jet current has not doubled with the use of two needles compared to the single-needle system. This may be due to the decreased electric field strength resulting in lower electrospun jet rate with thinner fibers.

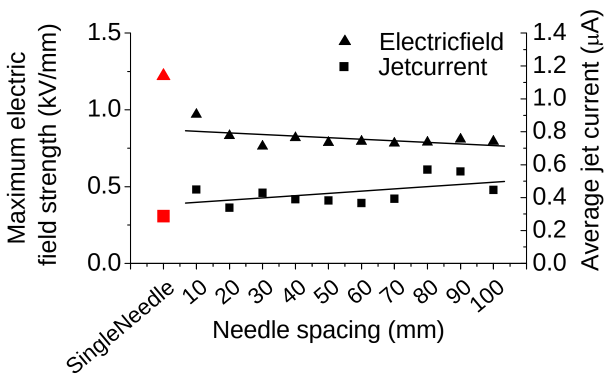

Fig.8. The variation in calculated maximum electric field strength and the average jet current of the electrospun jet for different needle spacing. For comparison, the test data for a single-needle arrangement is also shown.

C. Characteristics of fiber diameter

Figure 9 shows the variation of average fiber diameter with increasing gap distance between two needles. Similar to the variation of maximum electric field strength and the average jet current, the average fiber diameter does not change greatly with the increase of needle spacing. However, it was observed that the fiber diameter with 2-needle arrangement is thinner compared to the fiber produced using a single-needle system. There seems to be some controversy with electrospinning process as some researches have observed that the higher electric field lead to greater stretching of the jet resulting in thinner diameter fibers [4, 5, and 6]. In contrast Zhao et al. have verified that the weaker electric field strength reduces the acceleration of the jet and hence increases the flight time of the electrospinning jet; resulting in thinner fibers [7]. Our observation agrees with this and it might be due to the large distance (250mm) between the needles and the target. In addition it was difficult to obtain uniform fibers in all the cases due to the deterioration of local electric field.

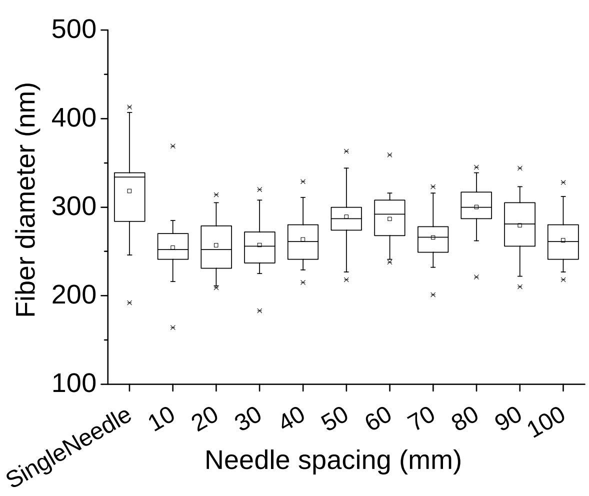

Fig.9. The variation in average fiber diameter of electrospun fibers for different needle spacing. For comparison, the test data for a single-needle arrangement is also shown.

V. CONCLUSION

The variation in electric field strength at the tip of the needles with a 2-needle arrangement was investigated using FEM analysis. The results were compared with a single-needle system and it was observed that the local electric field strength weakened significantly in the case of two needles due to mutual influence of electric fields around each needle tip. The spacing between the needles was varied and the effects of gap on electric field were simulated. The experimental results obtained using a 5% w/w PEO water solution in the fiber formation match with the calculated average maximum electric field at the needle tip/s. The degree of field distortion correlates with the variation in the measured vertical angle of the straight jet portion for different needle spacing. However the influence of needle spacing on average jet current and fiber diameter is not highly significant.

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