3-dimensional computer model of electrospinning multicapillary unit used for electrostatic field analysis

https://doi.org/10.1515/phys-2017-0132
Received November 2, 2017; accepted November 30, 2017

Abstract: Electrospinning is an experimental method of the polymer super thin fibres formation using the electrostatic field. The distribution of electrostatic field affects the effectiveness of the electrospinning. In order to analyse the electrostatic field for given technological parameters the 3-D computer model of an electrospinning device must be applied.

Keywords: computer model, electrospinning, electrostatic field, capillaries, nanofibres, finite elements method

PACS: 81.16.-c; 07.05.Tp; 41.20.Cv; 83.60.Np; 81.05.Lg

1 Introduction

Electrospinning is the process of producing super thin fibres from a solution or polymer alloy in an electrostatic field. The main properties of such fibres are their nanometer thickness, very large surface area to volume ratio, functionalisation possibility, and high tensile strength. Such properties allow using these fibres for many special applications where other forms of material cannot be used. Nanofibres have already found use in various areas of life. Many new nanofibres are being developed with unique properties and possible applications. Yet the problem concerns the production of nanofibres on an industrial scale. Among the various techniques of nanofibres (tensioning, template synthesis, molecular self-assembly, electrospinning), electrospinning is particularly desirable from the industrial use point of view. The main advantage of this technique is the ability to produce continuous filaments. The major disadvantage is instability of the spinning stream [1, 2]. It is still not cost effective, despite the fact that different electrospinning methods have been developed. The low production rate methods described in the literature are based on spinning in the electrostatic field by capillary-free methods, mostly from the open surface of the solution, or by conventional method from capillaries [3].

In the first case, increasing the open area on which the polymer streams are formed entails a risk of altering the properties of the spinning solution during the production of the nanofibres. The larger the surface of the solution is, the more favourable the conditions for faster evaporation of the solvent. For this reason, it is not advisable to spin from easily volatile solvent.

One of the solution surface methods but with no capillary was proposed by Yarin and Zussman. The system comprised the lower layer of ferromagnetic suspension and the upper layer of polymer solution. It was placed in magnetic field produced by a permanent magnet. The productivity rate from the solution surface was 12 times higher than from the conventional one capillary system [4].

A new method of multiple jets electrospinning with a rotating cylinder as a spinning head dipped at half-high in polymer solution was presented by Kameoka and Craighead [5], Lee [6], and Jirsak [7]. In Jirsak’s method the productivity was 1.5 g/min per 1 m of rotating cylinder with 30 mm in diameter and 1.8 g/min per 1 m of cylinder with 50 mm in diameter [8]. The NanospiderTM equipment for industrial scale nanofibre production by Jirsak’s method is manufactured by Elmarco s.r.o, Czech Republic [9].

The productivity rate of nanofibers can be enhanced 24-45 times, compared to a single-needle system, by splashing needleless electrospinning method investigated by Tang [10] and Nurwaha [11].

Another method (without capillaries but with the use of polyethylene cylindrical porous tube) was proposed by...
Dosunmu. The mass production rate of this multiple jets electrospinning was 250 times greater than by a conventional method [8].

In the latter case it is possible to produce fibres both from the polymer solution and from the polymer melt. While using a single capillary stand the productivity range is from 0.1 to 1.0 g/h of fibres, but sometimes it can vary depending on the solution properties and technological parameters of electrospinning process [8].

Tomaszewski and Szadkowski constructed the concentric multi-jet electrospinning head, which improves the efficiency and quality of the process. For poly(vinyl alcohol)/water solution the efficiency is 1 mg of dry PVA nanofibres from one spinning pipe during one minute [12].

2 Electrospinning process

The solution is stable in conventional method, while the polymeric trickle formed in the electrostatic field may be unstable. The initiation and behaviour of the polymer spiral is influenced primarily by the electrostatic forces acting therein, arising in the space between the delivery and receiving electrode [13, 14]. The polymer jet follows the path of the electric field’s current density lines [15]. Electrostatic field strength, depending on the technological, environmental and spinning parameters, also affects the morphology of the resulting fibres [16]. In spite of many investigations concerning electrospinning process, the dependence of the spinline and polymeric jet behaviour on electrostatic field is not clear. Most of the theoretical considerations on this subject are with one capillary system [13, 16, 17]. The electrostatic field distribution simulated for one single capillary electrospinning system is inhomogeneous concentrated on the surrounding area of the capillary. The influence of the electrostatic field distribution on the electrospinning process for one capillary stand and the fibre morphology was analysed by Yang [18]. Three kinds of electrostatic field: nonuniform, slightly nonuniform, and uniform were considered. These kinds of electric field depend on electrospinning apparatus. Wherever the capillary tip is located in plate or if the capillary tip juts out of the electrode plate. To describe the electrostatic field the average electric field strength and the electric field nonuniformity coefficient were applied. The electric field strength diminishes at the capillary tip and grows between electrodes It leads to more uniform electrostatic force affecting the polymeric jet.

In order to increase the productivity rate the system should be multicapillary. In such multicapillary systems the jet path depends not only on externally applied electric field which is as driving force, but also on self-induced Coulombic interactions and mutual-Coulombic interactions between different jets. Mathematical and theoretical modelling and simulating procedure can be very useful for physical understanding of electrospinning phenomena and for optimization of the factors affecting the productivity increase [19]. The modelling of field strength distribution for capillaries arranged uniaxially was carried out by Krucińska et al. [20]. The theoretical analysis of distribution of the electrostatic field forming around the spinning points in the area where polymer jets are formed and stretched was accomplished for changeable technological parameters of electrospinning, such as: distance between capillaries, distance between capillary tip and collector, and supply voltage. The simulations for changeable distances between capillaries arranged linearly and in 3 × 3 matrix were done by Theron et al. [21]. However, capillary-collector distance and applied voltage were the same in each case.

The process of a jet initiating and its stretching depends on the conditions determining the formation, magnitude and distribution of the electrostatic field between the adjacent capillaries and between the capillaries and the collector. These conditions are determined by the technological parameters of the electrospinning process, i.e. the voltage applied to the system, the distance between the tips of the capillaries and the collector, the distance between the capillaries, their distribution, the diameter, the length and the capillary material, the hydrostatic pressure in the capillary, shape of the collector, solution parameters such as viscosity, concentration, conductivity, surface tension, temperature and ambient parameters such as air temperature and humidity.

The problem of the conventional method is determined by the instability of the polymer jet in the electrostatic field and the process disturbance resulting from the inappropriate placement of the capillaries in the feed element and the inappropriate distance of the capillary from the receiving element. The main factor influencing the shape and flow of the polymeric jet is the electrostatic forces generated in the space between the delivery electrode and the receiving electrode. The deflection of the polymer solution jets flowing from adjacent capillaries can be the result of deformation of the electrostatic field formed around the outlets of the spinning points. Too close to each other the capillaries can lead to the screening of the electrostatic field.

In this paper the electrostatic field analysis was prepared in finite elements method package – Opera 3D.
3 Electrospinning experiment

Electrospinning is an experimental method of the polymer spinning by the electrostatic field.

The process of electrospinning from the polymer solution can be carried out by various methods differing in the apparatus used, capabilities, limitations, purpose, and especially efficiency. The conventional method called “from capillary” is the most common method of electrospinning. However, the productivity of this method in the case of application only one capillary is very low and ranges from 0.1 to 2 ml/h, while for the method “from the rotating roller” the process productivity is 1800 mg/min (for the roller with length of 1 meter and a diameter of 50 mm), for the method “from the porous tube” is 250 times greater, and for the method “from the open surface of the solution” is 12 times higher than that of the conventional method “from capillary”.

An important advantage of the conventional method “from capillary” compared to other methods, is the stability of the spinning solution and no preferences to type of fibre polymer applied [3–8].

The process of initiating a jet and its stretching depends on the conditions that determine the formation, magnitude and distribution of the electrostatic field between the capillaries and between the capillaries and the collector. These conditions are determined by the technological parameters of the electrospinning process, i.e. the voltage applied to the system, the distance between the capillaries and the collector, the distance between the capillaries, their distribution, the diameter, the length and the capillary material, the hydrostatic pressure in the capillary, shape of the collector, solution parameters such as viscosity, concentration, conductivity, surface tension, temperature and ambient parameters such as air temperature and humidity [20].

The electrostatic field created between the capillaries, from which the polymer flows, and grounded receiver, causes the natural transformation of the polymer droplets into a long, very thin fibres.

To design the multicapillary stand for electrospinning of a wide web of submicro/nanofibres the simulation of the electrostatic field influencing the course of the electrospinning from capillaries is necessary.

The considered multicapillary stand is equipped with a multi-track peristaltic pump, each of which is connected to one of the spinning capillaries, placed on the horizontal arm of the support structure. The spinning head contains 32 capillaries set in four rows, spaced 3 cm apart in row and 6 cm between rows. The distance between the capillaries was optimized using the mathematical modelling of the electrostatic field forming around the capillaries in the immediate vicinity of the others. The multicapillary stand allows to form the high oriented fleeces of fibres, what is possible because of a wide range of speed control of the spinning beam and the pickup drum [22].

4 3-dimensional computer model

For simplified electrospinning system from Figure 1 the computer model was prepared. Authors modelled capillary plate and drum, where the appropriate boundary conditions were applied.

The capillary plate gives the possibility of spinning through 32 holes. In practice, such a large number of spinning points cause disruption of the electrostatic field and as a result disruption of the process. For this reason, two different computer models have been prepared – one and two spinning capillaries accordingly. The applied voltage was 23 kV to the surfaces of the plate.

The drum, which is used to receive spun fibres, has been grounded. The analysis was conducted for different distances. The distances between the drum and the capillary plate were: 10 cm, 17.5 cm and 25 cm.

The most important part of above stand is dosing unit with capillary plate. As the most crucial part of the device the capillary unit has to be modelled very carefully and with lots of details.

In the computer model the Laplace equation of scalar electric potential \( \phi \) was used:

\[
\nabla \cdot \sigma \nabla \phi = 0
\]

The Dirichlet boundary condition can be described by equation (2). This condition was assigned to the background:

\[
\frac{\partial \phi}{\partial t} = 0
\]

Figures 3 and 4 present the computer model of particular case of analysis and meshed capillary plate. The finite elements mesh was generated from tetrahedral and hexahedral shape elements. The capillary plate demanded the densest mesh with high precisions. The computer model was prepared for several configurations. Although the current analysis was done for two cases (one and two capillaries). Thanks to creation universal model it is simple to regulate the value of supply voltage and the distance between the capillary plate and the drum. Further spinning capillaries may be easily added (supplied) in future researches.
5 Electrostatic field analysis - results

The following figures present distribution and lines of electromagnetic field for electrospinning system.

From preliminary observations, one can see how the electric field strength changes when the drum is displaced from the capillary plate and observe the shape of flux lines changes after adding extra capillaries.

The influence of the distance between capillary (-ies) and the receiving drum on the variations of the electric field strength for a single-capillary and double-capillaries electrospinning systems were computed and compared.

The Figures 5 and 6 depict changes of the electric field strength with the increase of the distance: a) 10 centime-
Figure 5: Electric field strength [V/m] for single-capillary set distances from drum: a) 10 cm, b) 17.5 cm, c) 25 cm

Figure 6: Electric field strength [V/m] for double-capillaries set distances from drum: a) 10 cm, b) 17.5 cm, c) 25 cm
tresses; b) 17.5 centimetres; c) 25 centimetres, between the capillary (-ies) and the receiver, respectively for the single-capillary set and the double-capillaries set.

As it can be seen in the Figures 5-6, the additional capillary influences the shape of the field force lines.

The electric field strength lines condense and their congestion increases along the x axis.

The displacement changes from 10 centimetres to 17.5 centimetres and finally to 25 centimetres result in decreases of the electric field strength value.

Furthermore, the flux lines along the z axis start to bend with the increase of the distance between the capillary (-ies) and the receiving drum. Generally, higher forces work between the components closer to each other.

6 Conclusions

This paper presents the first stage of co-operation among specialists in electrospinning and computer models. The aforesaid model is to be developed in the future. Electrospinning systems can be improved as a result of 3-D models application.

Acknowledgement: This research work was financed from funds assigned for 501/14-148-1-2117 statutory activity by Department of Material and Commodity Sciences and Textile Metrology, Lodz University of Technology, Poland.

References