

INTERFACIAL PROPERTIES AND PROCESS-STABILITY CRITERIA IN THE ELECTROSPINNING OF SILK FIBROIN SOLUTIONS: SURFACE TENSION, FIELD STRENGTH AND LOCAL FIELD ENHANCEMENT

Shohruxmirzo Mahsudov a*

Sherzod Korabayev a

Fayzulla Bekchanov b

Utkirbek Boboyev a

^a Namangan state technical university, Namangan, Uzbekistan

^b Kimyo International University in Tashkent, Tashkent, Uzbekistan

* Corresponding author. E-mail: shohruxmahsudov@gmail.com

Abstract

Electrospinning regimes are normally reported as an applied voltage and a working distance, and the surface tension of the spinning solution — the property those parameters must overcome — is usually quoted without an uncertainty estimate or omitted altogether. This work determines the surface tension of a silk fibroin / poly(vinyl alcohol) composite spinning solution by the stalagmometric method with a propagated uncertainty estimate, and relates it to the process regime through a physical analysis. The measured value is $\sigma = 62.39 \pm 1.22 \text{ mN m}^{-1}$ (relative uncertainty 1.96%), which is 14.8% below that of the reference liquid, a difference nine times the expanded uncertainty and therefore significant. Three distinct failure modes of the process were identified and traced to their physical causes: asymmetry of the Taylor cone, incomplete solvent evaporation in flight, and insufficient field strength to overcome surface tension. The stable regime corresponds to a mean field strength of 3.8 kV cm^{-1} , which is 3.4 times the mean of thirteen regimes reported in the tissue-engineering literature ($1.12 \pm 0.44 \text{ kV cm}^{-1}$) and is shown to follow from the exceptionally high viscosity of the solution. From the balance of capillary and electrostatic pressures, the local field at the Taylor-cone apex is estimated at approximately $2.4 \times 10^7 \text{ V m}^{-1}$, an enhancement factor of about 60 over the mean field, which quantifies the contribution of emitter-tip geometry to the critical condition. Because the local field scales as the square root of surface tension, the 14.8% reduction achieved by the ethanol component lowers the field required for jet initiation by 7.7%.

Keywords: Surface tension; stalagmometric method; measurement uncertainty; Taylor cone; field strength; local field enhancement; process stability; silk fibroin; electrospinning.



Introduction

The electrospinning process comprises three stages. In the first, an electric field acts on a droplet of polymer solution held at the tip of a capillary by surface-tension forces; mutual repulsion of like charges deforms the droplet into a cone — the Taylor cone — from whose apex a primary jet is ejected [1]. In the second, the jet undergoes bending instability, splits and is stretched while the solvent evaporates [2, 3]. In the third, the resulting fibres are deposited on the collecting electrode.

The stability of the first stage determines the outcome of the whole process. For a jet to form and be sustained, the electrostatic forces must overcome the surface-tension forces of the solution; at the same time the viscosity and surface tension must not be so low that the solution flows freely from the capillary. Surface tension is therefore, together with viscosity, one of the principal input parameters of the process [4].

As Taylor showed, when electrostatic and capillary forces are in equilibrium the semi-vertical angle of the cone is 49.3° ; this value is independent of the nature of the liquid and serves as a criterion for visual monitoring of process stability [1]. In practice, asymmetry of the cone or its complete failure to form indicates a mismatch between the properties of the solution and the parameters of the regime.

In the existing literature the value of surface tension is usually quoted without stating the measurement uncertainty, and the regime is described only in terms of voltage and distance, which makes results obtained on different installations difficult to compare. A further consequence of this reporting convention is that regimes lying far outside the usual range are not recognised as such, because a voltage and a distance that are individually unremarkable can combine into a field strength that is not.

The novelty of the present work lies in determining the surface tension of a silk fibroin composite spinning solution together with its propagated measurement uncertainty, in expressing the process regime in normalised form and comparing it quantitatively with the range reported in the literature, and in estimating the local field enhancement at the Taylor-cone apex from the capillary–electrostatic balance.

The aim of the work is to determine the surface tension of the final composite spinning solution with its uncertainty, to analyse the factors that disrupt the stability of electrospinning, and to justify physically the regime parameters that provide a stable process.

2. Materials and methods

2.1. Solution and equipment

The object of study was the final composite spinning solution consisting of 40% silk fibroin solution (0.2 g of fibroin per 5.5 g of solvent) and 60% of a 16% solution of poly(vinyl alcohol), Arkofil PPL grade; its dynamic viscosity is 2139.6 mPa·s and its total polymer content 11.0 wt%. The experiments were carried out on a Fluidnatek LE-50 laboratory electrospinning system (Bionicia, Spain), shown in Fig. 1.





Fig. 1. External view of the laboratory electrospinning system.

In this installation the solution is held in a syringe mounted on a pump and delivered through a capillary to a spinning head supplied with positive voltage; the nanofibres are deposited on a substrate fixed to a drum (the collecting electrode) supplied with negative voltage. The emitter voltage is adjustable from 0 to 30 kV and the collector voltage from 0 to -10 kV; the flow rate is adjustable from 0.1 to 1000 mL h^{-1} and the collector rotation speed from 100 to 2000 min^{-1} . The unit is equipped with a camera with an objective lens for observation of the Taylor cone and with temperature and humidity sensors.

2.2. Surface tension measurement

The stalagmometric method was selected. It is based on determining the mass of a drop that detaches under gravity from the flat cut surface of a capillary. At the moment of detachment the weight of the drop equals the surface-tension force acting around the circumference of the drop neck:

$$q = 2 \cdot \pi \cdot r_0 \cdot \sigma, \quad (1)$$

where r_0 is the capillary radius (m) and σ the surface tension (N m^{-1}). If the volume V of the expanded portion of the stalagmometer and the liquid density ρ are known, the weight of a single drop for n drops is

$$q = V \cdot \rho \cdot g / n, \quad (2)$$

whence

$$\sigma = V \cdot \rho \cdot g / (2 \cdot \pi \cdot r_0 \cdot n). \quad (3)$$

In practice the determination is made relative to a standard liquid of known surface tension, in which case V , r_0 and g cancel:

$$\sigma_x = \sigma_0 \cdot (\rho_x \cdot n_0) / (\rho_0 \cdot n_x). \quad (4)$$

The schematic of the measuring device is shown in Fig. 2.

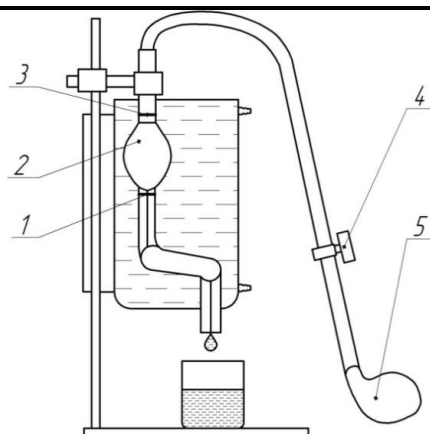


Fig. 2. Schematic of the stalagmometric device for determining surface tension: 1, 3 — marks; 2 — bulb; 4 — clamp; 5 — rubber bulb.

The expanded uncertainty of the result was estimated from Eq. (4) by the propagation rule for indirect measurements:

$$u(\sigma)/\sigma = \sqrt{[(u(n_x)/n_x)^2 + (u(n_0)/n_0)^2 + (u(\rho_x)/\rho_x)^2 + (u(\rho_0)/\rho_0)^2]}. \quad (5)$$

The discretisation uncertainty in drop counting was taken as ± 1 drop and that of the density determination as $\pm 0.001 \text{ g cm}^{-3}$.

The procedure was as follows. The stalagmometer was mounted on a stand so that the lower edge of the capillary was horizontal, and immersed in a thermostat. The liquid under test was poured into a beaker raised so that the tip of the capillary was immersed. Using a rubber bulb the liquid was drawn above the upper mark (3), avoiding the entry of air bubbles, and the clamp was closed. The beaker was then placed on the bench, the clamp opened carefully so that the liquid began to drip, and the drops were counted from the moment the level reached the upper mark until it reached the lower mark (1).

2.3. Normalisation of the regime

To express the regime in a form comparable between installations, the mean field strength between emitter and collector was computed as

$$E = (U_e + |U_c|) / H, \quad (6)$$

where U_e is the emitter voltage (kV), U_c the collector voltage (kV) and H the emitter-to-collector distance (cm).

3. Results

3.1. Surface tension and its uncertainty

Table 1 gives the measurements and the results computed from Eqs. (4) and (5).

Table 1. Determination of the surface tension of the final solution.

Parameter	Standard liquid	Final solution
Density ρ , g cm^{-3}	0.998	1.235
Number of drops n	62	90
Surface tension σ , mN m^{-1}	73.19	62.39
Relative uncertainty $u(\sigma)/\sigma$, %	—	1.96
Expanded uncertainty, mN m^{-1}	—	± 1.22

The surface tension of the final composite solution is therefore $\sigma = 62.39 \pm 1.22 \text{ mN m}^{-1}$. The density of the solution exceeds that of the standard liquid by 23.7% and the number of detached drops by 45.2%, while the surface tension is lower by 10.80 mN m^{-1} , that is 14.8%. This difference is almost nine times the expanded uncertainty and is therefore statistically significant.

3.2. Failure modes of the process and their causes

Preliminary electrospinning trials were carried out with spinning solutions 1.3, 2.3 and 3.3, which had the highest viscosities of the series. For these solutions three characteristic manifestations of instability were recorded; their physical causes and the corrective measures adopted are systematised in Table 2.

Table 2. Failure modes of the electrospinning process and corrective measures.

Manifestation	Physical cause	Corrective measure
Asymmetry of the Taylor cone	unstable meniscus shape at the capillary tip; insufficient viscosity	polymer concentration raised to 11.0 wt%, viscosity $\geq 2000 \text{ mPa}\cdot\text{s}$
Incomplete evaporation of the solvent	insufficient flight time; high ambient humidity	H maintained at 10 cm; humidity controlled at 40%
Insufficient field strength	electrostatic pressure does not overcome capillary pressure	opposite-polarity supplies: +29 kV and -9 kV, 38 kV in total

For the regime selected, Eq. (6) gives

$$E = (29 + 9) / 10 = 3.8 \text{ kV cm}^{-1}.$$

The complete set of regime parameters providing a stable process is given in Table 3.

Table 3. Parameters of the stable electrospinning regime.

Parameter	Value
Emitter-to-collector distance H	10 cm
Emitter voltage U_e	+29 kV
Collector voltage U_c	-9 kV
Mean field strength E	3.8 kV cm^{-1}
Spinning-solution feed rate	5 mL h^{-1}
Collector rotation speed	200 min^{-1}
Laboratory temperature	$20\text{--}22 \text{ }^\circ\text{C}$
Relative humidity	40%
Substrate	polyester lining fabric, $34 \times 19 \text{ cm}$
Deposition time per layer	30 min



Under these parameters the Taylor cone formed stably, no jet interruption or droplet formation was observed, the solvent evaporated completely over the flight distance, and homogeneous nanofibrous material samples were obtained.

4. Discussion

4.1. Origin of the measured surface tension

The surface tension of the composite solution is lower than that of water because of the ethanol component of the solvent: at 20 °C the surface tension of pure water is 72.8 mN m⁻¹ and that of ethanol only 22.3 mN m⁻¹, so ethanol acts as a strong surface-active component in aqueous systems. Calcium chloride acts in the opposite direction, since electrolytes slightly increase the surface tension of water. The measured value of 62.39 mN m⁻¹ is the resultant of these two effects and is qualitatively consistent with the composition of the mixture.

4.2. Capillary–electrostatic balance and local field enhancement

The balance of capillary and electrostatic pressures permits the physical limit of the process to be estimated. In a parallel-electrode approximation the electrostatic pressure is $p_e = \epsilon_0 E^2/2$; for $E = 3.8 \text{ kV cm}^{-1} = 3.8 \times 10^5 \text{ V m}^{-1}$ this gives $p_e \approx 0.64 \text{ Pa}$. The capillary pressure of a meniscus with apex radius of curvature r is $p_c = 2\sigma/r$; for $r = 50 \text{ }\mu\text{m}$, $p_c \approx 2.5 \text{ kPa}$. Equating the two pressures gives the local field strength required:

$$E_{\text{loc}} = \sqrt{(4\sigma / (\epsilon_0 \cdot r))} \approx 2.4 \times 10^7 \text{ V m}^{-1} = 237 \text{ kV cm}^{-1}, \quad (7)$$

that is, approximately sixty times the mean field. This result quantifies the established physical picture of electrospinning: jet formation occurs not through the mean field between the electrodes but through strong local concentration of the field at the capillary tip [1, 3]. The practical consequence is that the geometry of the emitter tip — needle diameter and tip shape — affects the critical voltage of the process on a par with the voltage itself and the working distance, and should therefore be reported alongside them.

Eq. (7) also shows that E_{loc} scales as the square root of σ . The reduction in surface tension from 73.19 to 62.39 mN m⁻¹ therefore reduces the field required for jet initiation by a factor $\sqrt{(62.39/73.19)} = 0.92$, that is by 7.7%. The ethanol component thus not only accelerates solvent evaporation but also lowers the energetic threshold of the process.

4.3. Dimensionless characterisation of the solution

Surface tension governs jet stability only in combination with viscosity and inertia, and the appropriate combination is the Ohnesorge number, which compares viscous forces with the geometric mean of inertial and capillary forces:

$$\text{Oh} = \eta / \sqrt{(\rho \cdot \sigma \cdot d)}, \quad (8)$$

where d is the characteristic dimension, here the internal diameter of the capillary. With $\eta = 2.1396 \text{ Pa}\cdot\text{s}$, $\rho = 1235 \text{ kg m}^{-3}$ and $\sigma = 0.06239 \text{ N m}^{-1}$, Eq. (8) gives $\text{Oh} = 14.1, 10.9$ and 8.6 for internal diameters of 0.3, 0.5 and 0.8 mm respectively. For comparison, a dilute polyester



solution of the kind used in most tissue-engineering studies ($\eta \approx 0.2 \text{ Pa}\cdot\text{s}$, $\rho \approx 1000 \text{ kg m}^{-3}$, $\sigma \approx 0.040 \text{ N m}^{-1}$) gives $Oh \approx 1.4$ at the same capillary diameter.

The interpretation is direct. $Oh \gg 1$ means that viscous dissipation dominates capillary forces, so that the Rayleigh–Plateau instability which would otherwise break the jet into droplets is strongly damped; continuous fibre formation rather than electrospraying is then the expected outcome. The timescale argument gives the same conclusion: the capillary breakup time $\sqrt{(\rho d^3/\sigma)}$ is 1.6 ms for a 0.5 mm capillary, whereas the viscous relaxation time $\eta d/\sigma$ is 17.2 ms, an order of magnitude longer. The jet is therefore stretched and solidified long before capillary instability can sever it.

This places the present solution in a distinct regime from most of the reported literature, with Oh roughly eight times higher, and it explains the two observations that would otherwise appear contradictory: the solution requires an unusually high field strength to initiate a jet, yet once initiated the jet is unusually stable. Both follow from the same high viscosity, acting against jet initiation at the meniscus and in favour of jet survival in flight.

The same framework accounts for the failure of the pure fibroin solution and of samples 1.3, 2.3 and 3.3. Their viscosities of 125–1336 mPa·s give Oh between 0.6 and 6.8 at a 0.5 mm capillary; the lowest of these lie near or below the threshold at which capillary breakup competes with stretching, which is consistent with the droplet deposits observed rather than fibres.

4.3. The regime in the context of reported practice

Comparison of the selected mean field strength with reported practice is instructive. A synthesis of thirteen electrospraying regimes reported for tissue-engineering scaffolds gives normalised field strengths in the range 0.56–2.00 kV cm⁻¹ with a mean of $1.12 \pm 0.44 \text{ kV cm}^{-1}$ and a median of 1.09 kV cm⁻¹ [5–8]. The value used here, 3.8 kV cm⁻¹, is 3.4 times that mean and lies more than six standard deviations above it.

This departure has a straightforward cause. The solutions in the reported studies are dilute polyester or protein solutions with viscosities typically one to two orders of magnitude below the 2139.6 mPa·s of the present composite; extracting a jet from a solution of such high viscosity requires a correspondingly larger electrostatic force. Expressed as voltage and distance — 29 kV at 10 cm — the regime appears unremarkable, and it is only when normalised by Eq. (6) that it is recognisable as an outlier requiring explanation. This is a direct argument for reporting the normalised field strength as a matter of course.

4.4. Critical voltage predicted from Taylor's criterion

The measured surface tension permits the critical voltage for jet initiation to be predicted rather than merely bounded. In Taylor's formulation, for a capillary of radius R and length L held at a distance H from the counter-electrode, the critical potential in the CGS system (V in kV, lengths in cm, σ in dyn cm⁻¹) is

$$Vc^2 = (4H^2/L^2) \cdot [\ln(2L/R) - 1.5] \cdot (0.117 \cdot \pi \cdot R \cdot \sigma). \quad (9)$$



Table 4 evaluates Eq. (9) for the range of capillary geometries available on the installation used (external diameters 0.15–3.2 mm, internal diameters 0.08–2.6 mm), at the working distance $H = 10$ cm employed here.

Table 4. Critical voltage predicted by Eq. (9) for the measured surface tension, and the effect of the ethanol-induced reduction in σ .

Capillary ID, mm	Capillary length L, cm	Vc at $\sigma = 62.39$ mN m ⁻¹ , kV	Vc at $\sigma = 73.19$ mN m ⁻¹ , kV	Reduction, %
0.30	2.0	11.9	12.8	7.7
0.50	2.0	14.3	15.5	7.7
0.80	2.0	16.9	18.3	7.7
0.50	1.0	25.7	27.8	7.7
0.50	3.0	10.1	10.9	7.7

Three conclusions follow. First, for the mid-range geometry (0.5 mm internal diameter, 2 cm capillary length) the predicted critical voltage is 14.3 kV, so that the applied emitter potential of 29 kV corresponds to an over-voltage factor of 2.03. Operating at roughly twice the critical voltage is consistent with established practice, in which a margin is required to sustain the jet against the viscous resistance of the solution rather than merely to initiate it — and the margin needed here is larger than usual precisely because of the high Ohnesorge number established in Section 4.3.

Second, the predicted critical voltage varies by a factor of 2.5 across the capillary geometries available on the same machine — from 10.1 to 25.7 kV — whereas the surface tension of the solution is fixed. Capillary geometry is therefore a stronger determinant of the critical condition than the interfacial property it is meant to overcome, which reinforces the argument of Section 4.2 that emitter geometry must be reported alongside voltage and distance.

Third, because Eq. (9) makes V_c proportional to $\sqrt{\sigma}$, the reduction in surface tension achieved by the ethanol component lowers the critical voltage by 7.7% for every geometry, exactly as the local-field argument of Eq. (7) predicted. The agreement between two independent routes to the same figure — a pressure balance at the cone apex and Taylor's integral criterion — supports the internal consistency of the analysis.

4.4. The role of bipolar electrode supply

Applying voltages of opposite sign to the emitter and the collector has two advantages. It allows the potential difference to be raised beyond the rating of a single supply — here to 38 kV using a 30 kV emitter source — and it simultaneously increases the efficiency with which fibres are collected, because the deposited fibres arrive at an electrode of opposite polarity rather than at a merely grounded one. This approach becomes particularly important when multi-emitter heads are used, since the emitter supply is then shared and its rating becomes the binding constraint on the achievable field.



4.5. Limitations

Three limitations should be stated. First, the stalagmometric method measures the equilibrium (static) surface tension, whereas the Taylor cone and the jet form on a timescale of milliseconds; over such intervals the diffusion of surface-active components to the interface may be incomplete, so the dynamic surface tension may exceed the measured value. Verification by a dynamic method such as maximum bubble pressure is recommended. Second, the estimate in Eq. (7) depends on the assumed apex radius of curvature ($r = 50 \mu\text{m}$) and should be regarded as an order-of-magnitude figure. Third, the specific electrical conductivity of the solution was not measured, although it is expected to be appreciable because of the high calcium chloride concentration and to affect the charge density carried by the jet; conductivity measurement would allow the electrostatic analysis to be extended from a pressure balance to a charge balance.

5. Conclusions

The surface tension of the final composite spinning solution was determined by the stalagmometric method together with its propagated measurement uncertainty: $\sigma = 62.39 \pm 1.22 \text{ mN m}^{-1}$ (relative uncertainty 1.96%), the solution density being 1.235 g cm^{-3} .

The surface tension is 14.8% lower than that of the standard liquid, a difference almost nine times the expanded uncertainty; the reduction is attributed to the surface-active effect of the ethanol component of the solvent.

Three failure modes of the electrospinning process — Taylor-cone asymmetry, incomplete solvent evaporation and insufficient field strength — were identified and traced to their physical causes, and a corrective measure was justified for each.

The mean field strength of the stable regime is 3.8 kV cm^{-1} , which is 3.4 times the mean of thirteen regimes reported in the tissue-engineering literature; the departure follows from the exceptionally high viscosity of the solution and is recognisable only when the regime is reported in normalised form.

From the capillary–electrostatic balance the local field at the Taylor-cone apex was estimated at approximately $2.4 \times 10^7 \text{ V m}^{-1}$, an enhancement factor of about sixty over the mean field, which quantifies the influence of emitter-tip geometry on the critical condition; since the local field scales as $\sqrt{\sigma}$, the measured reduction in surface tension lowers the field required for jet initiation by 7.7%.

The regime parameters providing stable operation were established as $U_e = +29 \text{ kV}$, $U_c = -9 \text{ kV}$, $H = 10 \text{ cm}$, feed rate 5 mL h^{-1} , collector speed 200 min^{-1} , $20\text{--}22 \text{ }^\circ\text{C}$ and 40% relative humidity.

Funding. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



Data availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

References

- [1] Taylor GI. Electrically driven jets. *Proc R Soc Lond A*. 1969;313(1515):453–75.
- [2] Hohman MM, Shin M, Rutledge G, Brenner MP. Electrospinning and electrically forced jets. I. Stability theory. *Phys Fluids*. 2001;13(8):2201–20.
- [3] Shin YM, Hohman MM, Brenner MP, Rutledge GC. Experimental characterization of electrospinning: the electrically forced jet and instabilities. *Polymer*. 2001;42(25):9955–67.
- [4] Fong H, Chun I, Reneker DH. Beaded nanofibers formed during electrospinning. *Polymer*. 1999;40(16):4585–92.
- [5] Zong X, Bien H, Chung CY, Yin L, Fang D, Hsiao BS, et al. Electrospun fine-textured scaffolds for heart tissue constructs. *Biomaterials*. 2005;26(26):5330–8.
- [6] Shin HJ, Lee CH, Cho IH, Kim YJ, Lee YJ, Kim IA, et al. Electrospun PLGA nanofiber scaffolds for articular cartilage reconstruction. *J Biomater Sci Polym Ed*. 2006;17(1–2):103–19.
- [7] Nesti LJ, Li WJ, Shanti RM, Jiang YJ, Jackson W, Freedman BA, et al. Intervertebral disc tissue engineering using a novel hyaluronic acid-nanofibrous scaffold (HANFS) amalgam. *Tissue Eng Part A*. 2008;14(9):1527–37.
- [8] Vaz CM, van Tuijl S, Bouten CVC, Baaijens FPT. Design of scaffolds for blood vessel tissue engineering using a multi-layering electrospinning technique. *Acta Biomater*. 2005;1(5):575–82.
- [9] Deitzel JM, Kleinmeyer J, Harris D, Beck Tan NC. The effect of processing variables on the morphology of electrospun nanofibers and textiles. *Polymer*. 2001;42(1):261–72.
- [10] Filatov YuN. Electroforming of fibrous materials (EFV process). Kirichenko VN, editor. Moscow: Karpov Institute of Physical Chemistry; 1997.
- [11] Petrov AV, Simonov-Emelyanov ID, Filatov YuN. Critical parameters for the evaluation of polymer solutions for the electrospinning of fibres. *Vestnik MITHT*. 2012;7(5):103–7.
- [12] Sukigara S, Gandhi M, Ayutsede J, Micklus M, Ko F. Regeneration of Bombyx mori silk by electrospinning. Part 1: processing parameters and geometric properties. *Polymer*. 2003;44(19):5721–7.
- [13] Doshi J, Reneker DH. Electrospinning process and applications of electrospun fibers. *J Electrostat*. 1995;35(2–3):151–60.
- [14] Reneker DH, Chun I. Nanometre diameter fibres of polymer, produced by electrospinning. *Nanotechnology*. 1996;7(3):216–23.
- [15] Ajisawa A. Dissolution of silk fibroin with calcium chloride/ethanol aqueous solution. *J Seric Sci Jpn*. 1998;67(2):91–4.
- [16] Zhang X, Reagan MR, Kaplan DL. Electrospun silk biomaterial scaffolds for regenerative medicine. *Adv Drug Deliv Rev*. 2009;61(12):988–1006.
- [17] Dorati R, Chiesa E, Pisani S, Genta I, Modena T, Bruni G, et al. The effect of process parameters on alignment of tubular electrospun nanofibers for tissue regeneration purposes. *J Drug Deliv Sci Technol*. 2020;58:101781.



- [18] GOST 18300-87. Rectified technical ethyl alcohol. Specifications.
- [19] GOST 6709-72. Distilled water. Specifications.
- [20] McKinley GH, Renardy M. Wolfgang von Ohnesorge. Phys Fluids. 2011;23(12):127101.
- [21] Yarin AL, Koombhongse S, Reneker DH. Taylor cone and jetting from liquid droplets in electrospinning of nanofibers. J Appl Phys. 2001;90(9):4836–

