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Influence of solvents on a near-field electrospun straight fine fibre

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Abstract. Near-field electrospinning (NFES) has been pursued in additive manufacturing for the fabrication of artificial extracellular matrix with controlled pattern structures from a continuous straight fine fibre. Due to short flight time, achieving a deposition of a solidified straight fine fibre can potentially be affected by the properties of a solvent. Therefore, this article presents an investigation of the effects of solvents on an NFES straight fine fibre. Dichloromethane (DCM), acetone, chloroform, toluene and dimethylformamide were the five solvents in this investigation. They were tested at the standoff distances of 3, 5 and 10 mm, and by using the needle gauges of 22G, 24G and 26G. According to the results, DCM having a relatively low boiling temperature and moderate dielectric constant delivered the smallest diameter straight uniform fibre. Furthermore, a solvent having a moderate boiling temperature and low dielectric constant is expected to deliver a thinner straight uniform fibre.

Keywords. ESRP; near-field electrospinning; scaffold; boiling temperature; solvents; dielectric constant.

1. Introduction

Effortless ability to produce a continuous fine fibre has gained electrospinning recognition for its applications in advanced research at microscale and nanoscale. Electrospun fibres are of interest because they are very fine and long, can be produced from various kinds of materials and have a high area to volume ratio. They have been utilized in a wide range of applications, including but not limited to filtration, textile and medical [1–3], especially for tissue engineering that covers more than 40% of advanced applications of nanofibres [4] where they are used to form scaffolds to support cell attachment, proliferation and differentiation [5].

An electrospun fibre is created by supplying high electrical voltage to a polymer solution or polymer melt. An electric field formed induces charge onto a polymer droplet held in place by surface tension at the tip of a needle. The accumulated charge strengthens the electrostatic force leading to the stretching of the droplet to a conical shape, and once the attractive force, the force between accumulated charge on droplet and the collector plate, overcomes the surface tension, the solution jet comes out from the crest of the cone. The jet travels in the air and undergoes into a solidification process during the flight before landing on a collector [6]. For conventional far-field electrospinning (FFES), commonly seen in practice, the needle and collector are typically placed several centimetres apart. With this long distance, the jet experiences both stable and unstable states. The stability of the flight depends upon the competition between the surface tension and repulsive force on the jet [7,8]. The jet flies straight initially because the surface tension on the jet is higher than the repulsive force. As the flight continues, more charge is collected on the surface of the fibre jet, and instability occurs which leads to bending right after the repulsive force becomes higher. A coil is formed with an increased diameter, but after a few turns, the fibre is stretched [9]. Whipping action stretches the fibre to a large extent up to a few centimetres, and during fibre stretching, a large amount of solvent evaporates to the environment [10]. Beyond this range, the fibre experiences a slow stretching and lands on the collector in a random spiral form to form a non-woven mat. The diameter of the collected fibre is generally 1.3×10^{-3} times of the jet [2].

Although non-woven mat from FFES might be applied for various applications including filtration, the random architecture might not be suitable for tissue engineering application. It hinders the flow of nutrients and gases as well as reduces the penetration of cells in the scaffold structure [11]. As a result, the cells tend to accumulate on the surface instead of growing inside the scaffolds [12].

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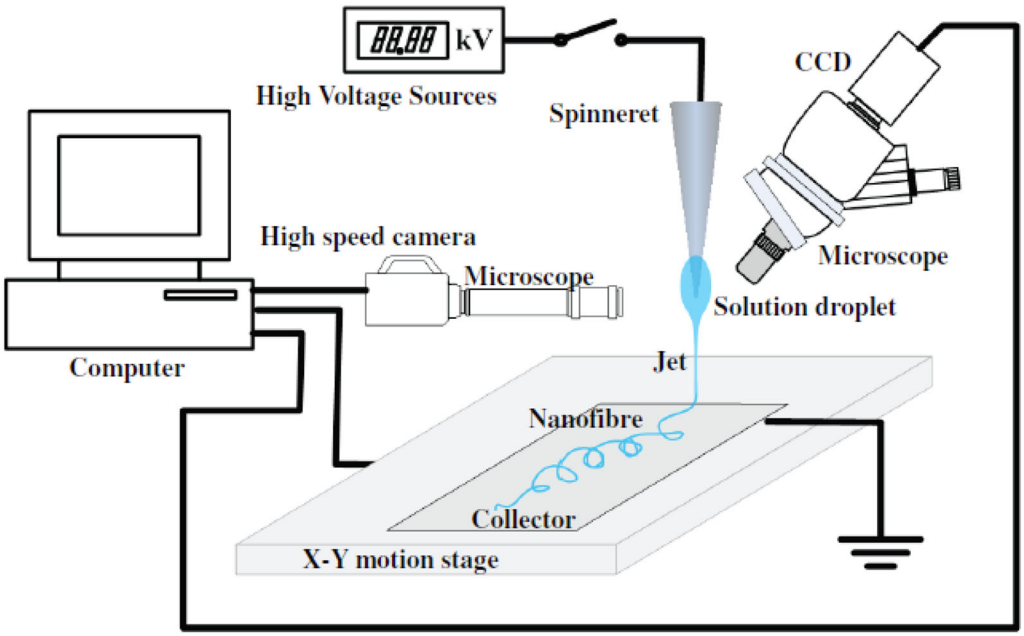


Figure 1. The schematic diagram of near-field electrospinning process [19].

Electrospinning, however, remains attractive because of the ability of electrospun fibres to imitate the fibre structure of natural extracellular [13]. Furthermore, the characteristics of the scaffolds can be controlled by tuning the fibre morphology [14]. Researchers have exploited these abilities by using electrospinning to create fine fibres attached to scaffolds built with controlled architecture by additive manufacturing techniques [9,15,16]. Electrospinning is also attractive to nano-electronics, electro-optical and sensors applications, but the random deposition cannot achieve required predetermined patterns [17]. Researchers have attempted to remove the random deposition of FFES by replacing the stationary collector with a rotating mandrel collector and controlling its speed and movement [18], by dampening the instability of the fibre jet with manipulating auxiliary electric fields [2] and by delaying the bending instability with a solvent selection [8]. These attempts can achieve the fibre alignment, but controlling the deposition on the desired positions remains a challenge.

Near-field electrospinning (NFES) was introduced as an alternative to FFES to achieve the deposition of direct continuous and controllable fibres [20]. With a similar setup, the jet is limited to experience only the stable flight by the shortening of the standoff distance (SOD) to be within millimetre range. Without bending instability, the fibre stretching depends mainly upon the speed of the collector. The fibre diameter decreases as the speed of the collector increases [21–23]. By controlling the movement of the collector, the fibre can be deposited at the desired location and forms a pattern. The ability to deposit a fibre in a control fashion not only allows electrospinning to be applied in electronic applications, but also opens up an opportunity to pursue the direct fabrication of controllable architecture scaffolds from continuous fine fibres. Figure 1 describes the schematic diagram of near-field electrospinning.

Recently, researchers have proposed to construct a scaffold layer by layer from a continuous fibre that is drawn by NFES instead of being extruded, as when fused deposition modelling (FDM) is applied [12,24,25]. The repeatability and reproducibility of the pattern creation of NFES have been reported, but because of the short SOD, the fibres deposited in a liquid state and flattened on the collector instead of forming cylindrical shape when they were electrospun from a polymer solution [25]. The flat ribbon-shaped fibre did not help to build the scaffold in the third dimension. There were also reports of achieving much better controlled shape of the fibre [26] and the height of scaffolds [12] for the high concentration level of a solution. Besides, high gauge needle was used when the temperature is maintained at 25°C during the process to obtain small cylindrical fibres [26]. Further investigation reported a reduction of the fibre diameter with the increase of the SOD, while the effects of airflow and relative humidity were slightly unclear on the diameter and the deposition precision [27].

The polymer jet leaves the needle tip with a cylindrical shape [28] and should be solidified when it reaches the collector to maintain its shape, which can be done by extending the SOD to allow more time for the fibre to solidify before arriving at the collector and/or by speeding up the solidification of the fibre. Both approaches to a certain extent can be influenced by the properties of a solvent. The dielectric constant of a solvent was reported to have an influence on bending instability [8]. When available free charge in the solution is low, more time is required to

initiate bending instability. As a result, a long straight jet can be achieved. Boiling temperature, on the other hand, has an influence on the solidification process. Low boiling point solvent evaporates quickly, which also allows fibre to solidify quickly. However, if the fibre solidifies too quickly, bending instability will be initiated early, as reported in the experiment of Bain and Koomsap [29].

It seems that the selection of a solvent will play an important role in 3D fabrication with NFES, but the limited number of research were reported in this particular area. Therefore, several experiments have been conducted to examine the impact of solvents on the fabrication of fibre with NFES.

2. Literature review

As aforementioned, the electrospun fibres are of interest because they are small and long, and have a high surface area to volume ratio. The ideal target for each of these fibres is that it is a defect-free continuous fibre with a consistent and controllable diameter. Achieving the target, however, is not easy because the characteristic of the fibre is influenced by several parameters that include solution properties, process parameters and ambient conditions [30]. A wide range of investigations have been conducted both theoretically and experimentally on various types of materials for conventional FFES. Thompson and colleagues [10], for instance, studied the effects of thirteen parameters on the fibre diameter from an electrospinning theoretical model. The results are summarized in table 1. Out of these thirteen parameters, only SOD, elongational viscosity and solution density influence the diameter reduction.

Among the five major influence parameters, only SOD can be directly controlled. The other four are achieved by controlling other independent parameters. The initial jet radius can be influenced by the inflow and outflow of the droplet. The competition between demand and supply causes a change in the shape and volume of the droplet [7]. Relaxation time represents the ability of a material to recover from stress state. It depends upon the properties of the polymer used. When the polymer concentration increases, this time will increase [31].

Volumetric charge density is the amount of electric charge per unit volume. In electrospinning, it is the amount of charge carried by jet relative to the jet's volume. It is a function of many parameters, including electric potential, flow rate, SOD, solution concentration, conductivity and polymer molecular weight. According to Theron and colleagues [7], volumetric charge density increases when the electric potential increases. It is trivial as more charge is introduced to the jet. A similar trend can be observed for solution concentration and molecular weight, which relate to the conductivity of a solution and polymers. Conductivity increases as the polymer concentration increases [31,32]. On the other hand, it decreases when the flow rate increases because more solution is used for carrying the same amount of charge. Similarly, volumetric charge density decreases when the SOD increases as the electric field strength decreases.

Viscosity represents the resistance of a fluid to deform by an external force. It depends upon temperature, pressure and solution concentration. It is important to characterize the fibre morphology [33]. When the viscosity is low, the continuous fibre cannot be obtained due to low entanglement. The jet cannot be formed either when the viscosity is too high. Furthermore, there are two types of viscosity: zero-shear viscosity and elongational viscosity [10]. The first one is referred to commonly. Its high value results in a large fibre diameter because more material is in the jet, and the obtained fibre also has a more consistent diameter [34]. The elongational viscosity reflects the stretching capability of the polymer solution. The solution with high elongational viscosity can withstand high voltage applied; as a result, the fibre can be stretched further without breaking. This leads to a small fibre diameter.

Since the zero-shear viscosity is proportional to the polymer concentration, increasing the polymer concentration will enlarge the fibre diameter [35]. This also means a minimum entanglement concentration exists for fibre-forming. A continuous fibre cannot be achieved unless the concentration of polymer solution is above the critical entanglement concentration [36].

The SOD applied in electrospinning ranges from 7 to 50 cm [10]. It provides enough flight time to evaporate the solvent and elongate the jet, so the solid fibre will be deposited on the collector. More importantly, it allows more charge to accumulate on the fibre, which leads to bending instability. Therefore, the longer the SOD is, the smaller the fibre diameter will be.

Electric potential is another important parameter. It induces charge onto a droplet, stretches the droplet and

Table 1. Parametric classification based on impact level on fibre diameter [10].

Major influence parameters	Moderate influence parameters	Minor influence parameters
Initial jet radius	Initial polymer concentration	Vapour diffusivity
Volumetric charge density	Perturbation frequency	Relative humidity
Standoff distance	Solvent vapour pressure	Surface tension
Initial elongational viscosity	Solution density	
Relaxation time	Electrical potential	

initiates a jet. Surprisingly, the influence of voltage on the fibre diameter is unclear. Some studies reported the decrease in the diameter when a high voltage was supplied [37], while others reported an insignificant effect on the diameter [38]. They are also contradicted with the result of the theoretical model. This might be because the electric potential is not the real influencer, but SOD and elongational viscosity are instead. At low voltage, less amount of material is pulled out by the electric field, so the diameter is small. When the charge density increase due to the increase of voltage, the jet diameter also increases. However, the reduction of fibre diameter occurs when bending instability occurs, which requires enough SOD for the charge to accumulate. The reduction rate depends upon elongational viscosity.

The solvent used for dissolving polymers has a direct influence on many of these parameters. As aforementioned, dielectric constant and boiling temperatures have influences on the bending instability and solidification of fibre respectively. They both also have influences on the diameter of the fibre. The jet experiences a rise in the charge density with the increasing dielectric constant, which creates a high stretching force and results in a fine fibre. High boiling temperature allows time for more charge to be collected on the jet, leading to long stretching before complete solidification which has been confirmed by several experimental investigations. A wide range of solvents such as dichloromethane (DCM), trifluoroacetic acid (TFA), tetrafluoroethylene (TFE), hexafluoroisopropanol (HFIP), chloroform, ethanol, dimethylformamide (DMF) and water have been investigated for electrospinning fibres from different polymers such as poly-L-lactide (PLLA) [39], polyethylene oxide (PEO) [40], polycaprolactone (PCL) [41,42] and polystyrene (PS) [43]. The results were similar that the fibre diameters reduced when the boiling temperature increased. The diameters also reduced when dielectric constant increased.

In the case of NFES, there have been experimental investigation reports on the influence of parameters on the fibre diameter. Voltage, concentration, SOD, needle size, speed, environmental condition, relative humidity, flow rate and the composition of mixed solvent have been the studied parameters. However, the number of reports is relatively small compared to the works on FFES. Furthermore, there was also a contradiction in the results obtained. For voltage, one study reported a slight increase in the diameter when a higher voltage was supplied to a superelastic polymer solution [30], while another reported insignificant effect on the diameter for melted PCL [23]. The increased fibre diameter was obtained with the increased inner diameter of the needle, i.e., low gauge needle for both PCL in DCM/DMF mixed solvents [28] and melted PCL [23]. However, the low gauge of needle reported to have no effect on the fibre size for PCL in acetic acid, but the increase in the concentration and its combination with electric field strength did affect the increase in the fibre size [44]. The increase in speed reduced the fibre size [20–23]. Similar results were also for SOD [26] and flow rate [23].

A recent study by Parajuli and colleagues [26] reported the relationships between near-field electrospun fibres from PCL in DMF and their polymer jets. According to the report, the variation of voltage did not affect a significant change in both jets' and fibres' diameters, and the fibres' diameter were about three times larger than their jets' diameter. In addition, there was a significant effect of SOD on the diameter of the jet and the diameter of the fibre. The diameters of the jets reduced as the SOD increased, but the fibres remained about three times larger than the jets. The fibres became smaller and got closer and closer to their jets when the concentration was increased and the temperature was maintained during the process. Last but not least, the thin diameter fibres were obtained for higher gauge of the needle.

3. Investigating the influence of solvents on NFES

According to Bain and Koomsap [29], polymer jets reacted differently for the different compositions of DCM/DMF mixed solvents in their NFES investigation. Because of much different boiling points between DCM and DMF, all DCM with much lower boiling point evaporates first from the mixed solvent before the evaporation of DMF. Instability bending occurred for the mixed solvents with a high amount of DCM that also has a lower dielectric constant. With a higher chance of having bending instability, the fibres were also smaller. The results seem to be the opposite of FFES. Therefore, experiments were carried out to study the influences of the properties of solvents, specifically on boiling temperature and dielectric constant, on the pattern creation and the fibre diameter.

3.1 *Experimental plan*

In this study, all fibres were made from PCL with Mn 45000 g mol^{-1} from Sigma Aldrich Chemistry. PCL was investigated with five different solvents: N,N-dimethylformamide (DMF) from QReC, dichloromethane (DCM) and acetone

Table 2. Boiling temperatures and dielectric properties of studied solvents.

Solvent	Boiling temperature (°C)	Dielectric property
DCM	39–42	8.93[a]
Acetone	56.3	20.7[b]
Chloroform	61.2	4.77[a]
Toluene	110.6	2.38[a]
DMF	153	36.71[a]

[a]Dielectric property at 25°C.
[b]Dielectric property at 20°C.

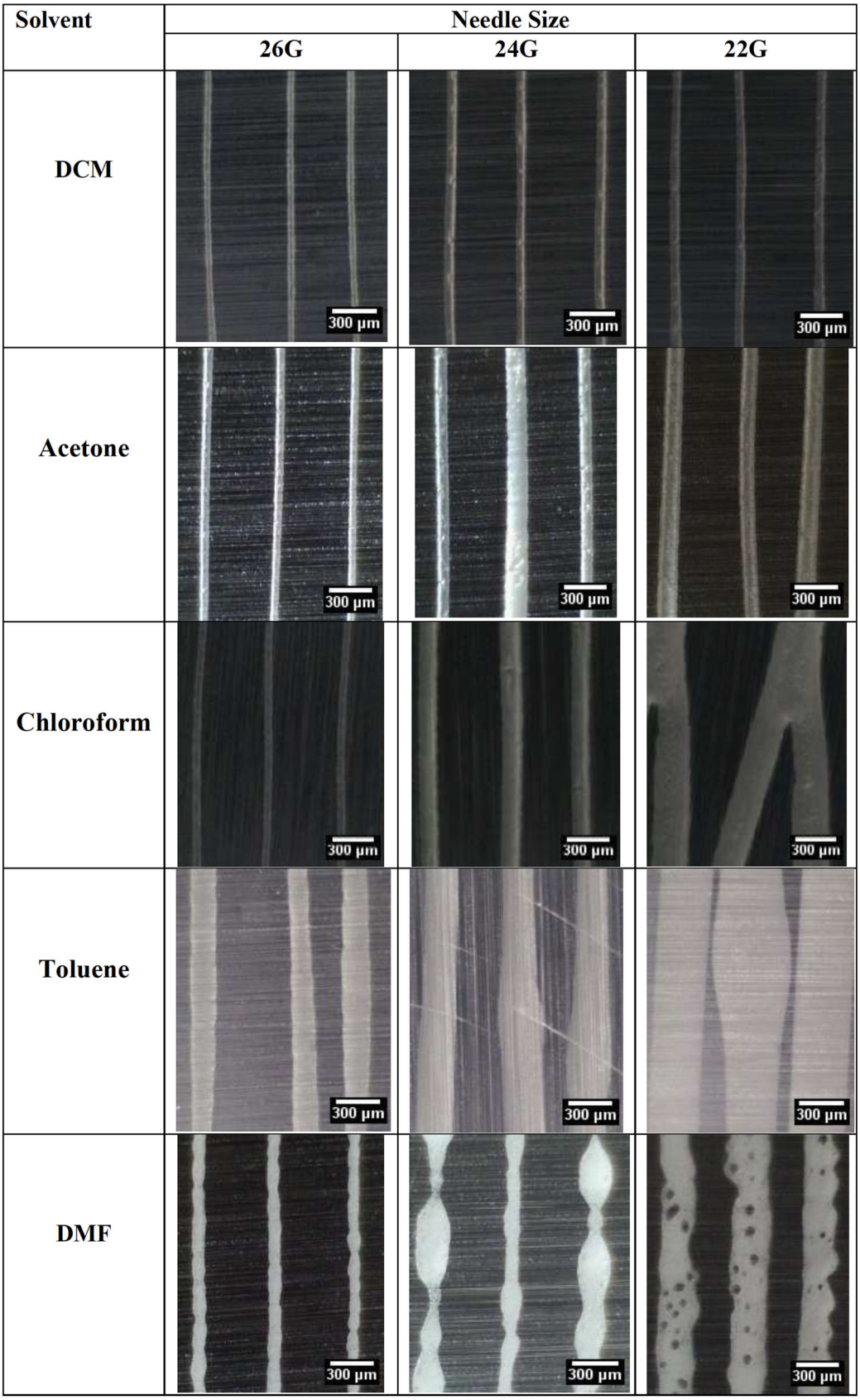


Figure 2. Examples of PCL fibres created when the SOD was 3 mm and the voltage was 2.6 kV.

from eMerckKGaA, chloroform and toluene from RCI Labscan. The boiling temperatures and the dielectric properties of the solvents are displayed in table 2.

For each of the solvents, nine combinations from the three levels of SOD (3, 5 and 10 mm) and of needle gauge (22G, 24G and 26G) were experimented. The inner diameters of the needle were 413, 311 and 260 μm.

Each combination of the three factors was experimented three times. The total numbers of experiments and samples were 45 and 135, respectively.

3.2 *Material preparation*

The solutions used in the experiments contained 70% (w/w) of PCL in the five different solvents. They were weighed on a digital scale. For each solution, both substances were mixed together on a hot-plate stirring machine set at different temperatures and times. For DCM, chloroform and toluene, the solutions were stirred for 3 h at room temperature. For acetone, the solution was stirred until PCL was completely dissolved at 40°C before cooled down to room temperature. For DMF, the solution was heated at 80°C for 15 min before cooled down to room temperature.

3.3 *Machine setup*

For each experiment, aluminium foil was used as a collector attached to an *X*–*Y* movable platform. The positive line of the power supply was connected to the needle, while the ground line was connected to the collector. The collector speed was constant at 200 mm s^{-1} with acceleration and deceleration of 50 mm s^{-2}.

3.4 *Sample*

All samples were single layer created along the *Y*-axis. Their size was 15 mm × 20 mm with 500 μm gap size.

3.5 *Evaluation method*

The fibres' diameters were measured from their images. The diameters of the fibres were calculated relative to the known diameters of the needles taken under the same conditions. For each experiment, the average diameter was calculated from its three random fibres, of which three measurements were made at three positions: head, middle and tail. A portable USB microscope with the magnification range of 20–800× was used for capturing the images. The resolutions were varied from 2.73 μm per pixel to 2.96 μm per pixel.

4. Results and discussion

PCL solutions in five solvents, DCM, acetone, chloroform, toluene, DMF, were prepared with 70% (w/w) concentration at SOD 3, 5 and 10 mm to investigate the effect of solvents' boiling temperature and dielectric constant on fibre morphology. Figure 2 shows the examples of PCL fibres created from the solutions of the five solvents using three different needle sizes when the SOD was 3 mm above the collector, and the voltage was 2.6 kV. All fibres were straight, but the low boiling temperature solvents (i.e., DCM, acetone and chloroform) delivered smaller fibre diameter than the high boiling temperature solvents (i.e., toluene and DMF). According to Hansen Solubility parameter the δt value of polymer PCL and solvents DCM, acetone and chloroform are very close, which represents that these solvents are good solvents for PCL [45]. When these low boiling temperature solvents exposed to the atmosphere, they evaporated quickly and allowed the jet to solidify and transform to be the fibres on the fly. On the other hand, the high boiling temperature solvents required much more time to evaporate, leading to the liquid deposition on the collector that later spread and formed the ribbon-shaped fibres. This is because, at low SOD the transformational ratio, i.e., the ratio of fibre diameter and jet diameter becomes high as the solvent cannot evaporate

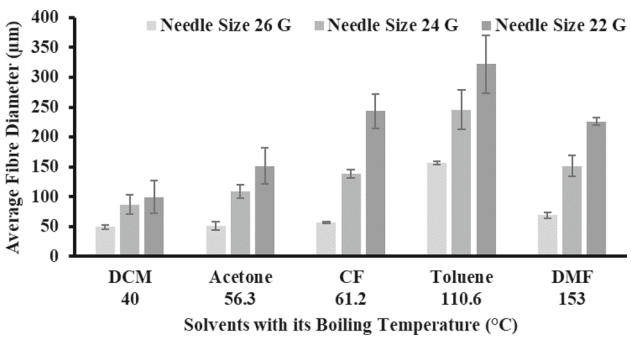


Figure 3. The effect of boiling temperature of five different solvents on fibre diameter with three different needle gauge size at SOD of 3 mm. Error bars represent the standard deviation in the data.

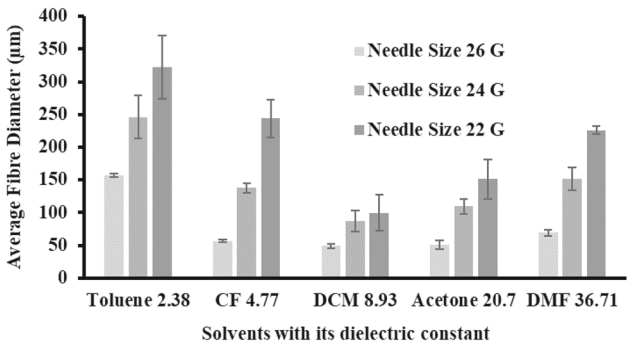


Figure 4. The effect of dielectric constant of five different solvents on the fibre diameter with three different needle gauge size at SOD of 3 mm. Error bars represent the standard deviation in the data.

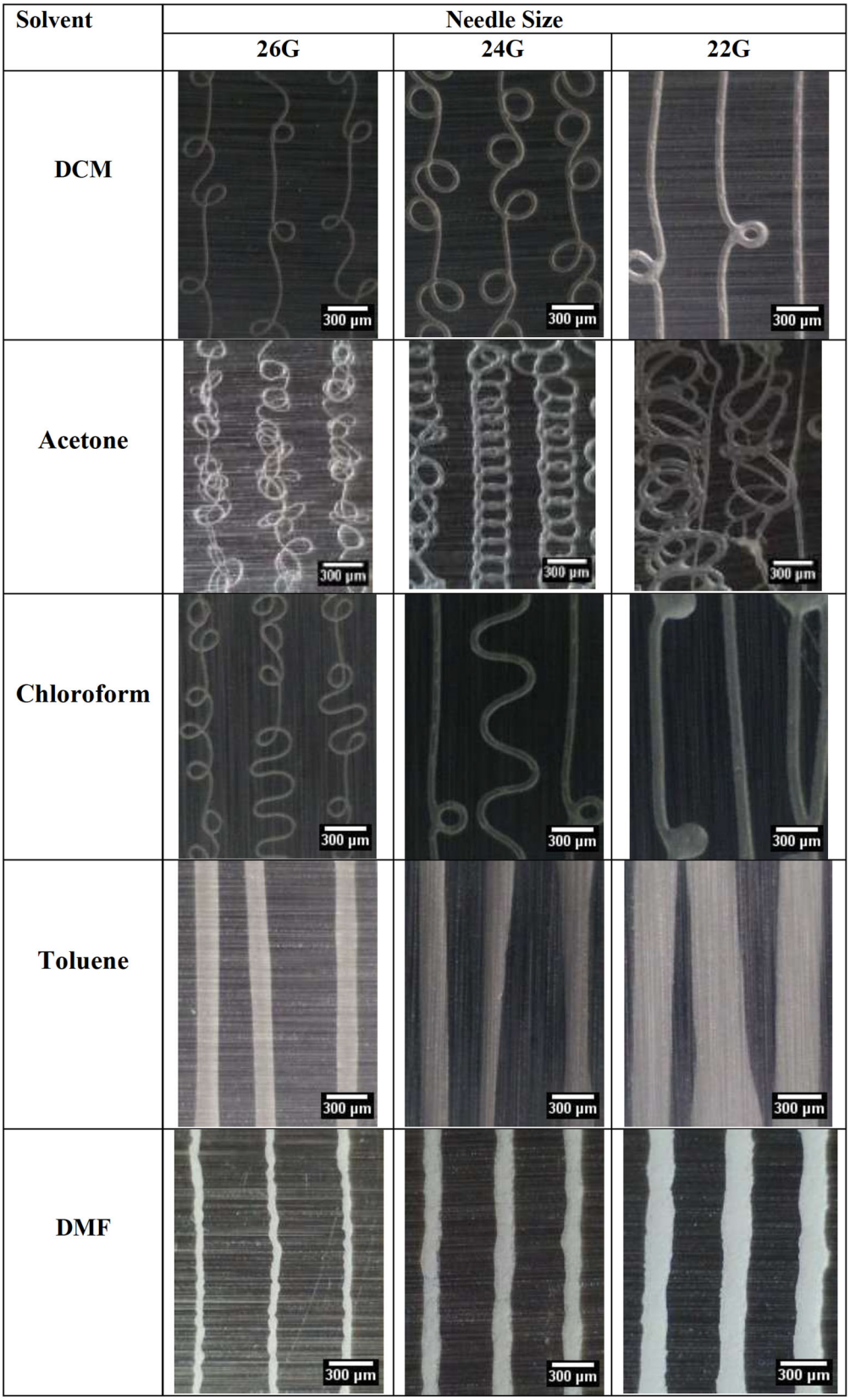


Figure 5. Examples of PCL fibres created when the SOD was 5 mm and the voltage was 3.5 kV.

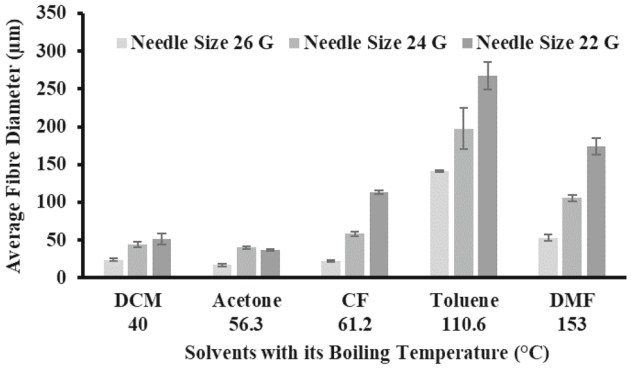


Figure 6. The effect of boiling temperature of five different solvents on fibre diameter with three different needle gauge size at SOD of 5 mm. Error bars represent the standard deviation in the data.

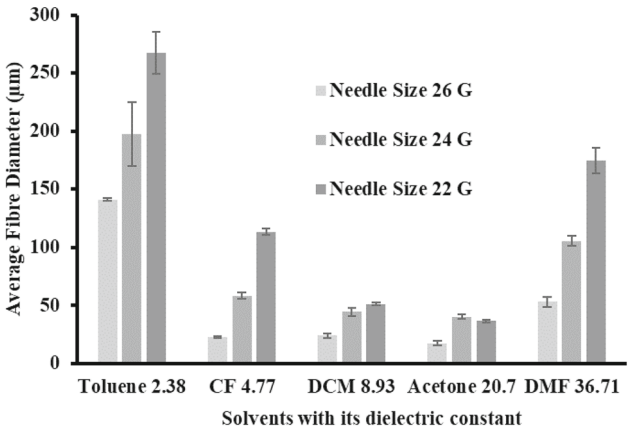


Figure 7. The effect of dielectric constant of five different solvents on the fibre diameter with three different needle gauge size at SOD of 5 mm. Error bars represent the standard deviation in the data.

quickly from the polymer part [25]. The average diameters of the obtained fibres are displayed in figure 3. It was observed that the diameter of the fibre is directly proportional to the boiling temperature of the solvent, although this trend was not followed by the high boiling temperature solvents. The fibres diameter obtained from DMF were smaller than toluene even though DMF has higher boiling temperature than toluene. The liquid jets with toluene spread easier than with DMF because of the dielectric property of the solvents.

The dielectric constant of a solvent plays role in accumulating charge in a solution. This not only helps to overcome the surface tension at the needle tip for initiating the jet formation, but also stretches a fibre. Figure 4 shows the relationships between the fibre diameter and the dielectric constant of the five solvents. At this short SOD, the dielectric constant of any solvents did not influence on stretching of fibre. With a high dielectric constant, the jet from DMF solution accumulated more electric charge during the fibre-forming process. This electric charge increased the electrostatic attraction between the molecules of the liquid jet and restricted it to flow even though it deposited in the liquid phase. Whereas, toluene has very low dielectric constant so it required time to form a fibre as well as flows quickly after deposited on collector because of insufficient bonding force on molecules to resist the flow.

The results also confirmed that the diameter of the fibre is directly proportional to the needle size. The needle diameter controls the volume of a solution, which directly affects a jet diameter. A small volume led to a small jet resulting in a small fibre. Besides, similar trends were obtained for the three different sizes of the needles. For this group of experiments, DCM has the lowest boiling temperature and moderate dielectric constant relative to the other four solvents that delivered the smallest straight fibres.

Figure 5 shows another set of examples of PCL fibres created from the solutions of the five solvents using the same three different needle sizes when the SOD was 5 mm above the collector, and the voltage was 3.5 kV. The result shows that all fibres created from the solution with the low boiling temperature solvents changed from a straight line to a coiled shape. The SOD 5 mm contributed to extend the flight time, which was sufficient for generating the whipping effect on the formed fibres that became more conductive. This phenomenal is relevance to the dielectric property of the solvents. The fibres obtained from acetone, a high dielectric constant solvent, experience higher whipping effect than the low dielectric constant solvent DCM and chloroform, and experienced smaller diameter for all gauges of the needle. Although chloroform has low dielectric constant, it produced smaller diameter fibre with high needle gauge 26G than DCM with the same needle gauge. On the other hand, the fibres from chloroform experienced large diameter with low needle gauge in contrast with DCM. This is because the 26G needle contains low volume of solution and in the case of DCM has low boiling temperature and evaporates quickly leading to solid fibre that cannot be stretched further. On the contrary, in the case of chloroform, with the same needle gauge, which has a high boiling temperature than DCM cannot evaporate quickly helps to stretch the fibre. The boiling temperature is more influent for the increased volume of solution. For DMF and toluene, the jet remained in a liquid state after deposition onto the substrate as these have very high boiling temperature compared to others and all the fibres remained straight. The effect of boiling temperature and dielectric constant on the fibre diameter at SOD of 5 mm are shown in figures 6 and 7.

Figure 8 shows the last set of examples of PCL fibres created from the solutions of the five solvents using the same three different needle gauges, where the SOD was kept at 10 mm above the collector, and the voltage was 4.2 kV. The result depicts that at this SOD DCM can produce small diameter fibre compared to previous two SOD at 3 and 5 mm but fibre deposited in coil form. This is because, at long SOD jet gets enough time to travel and the charge

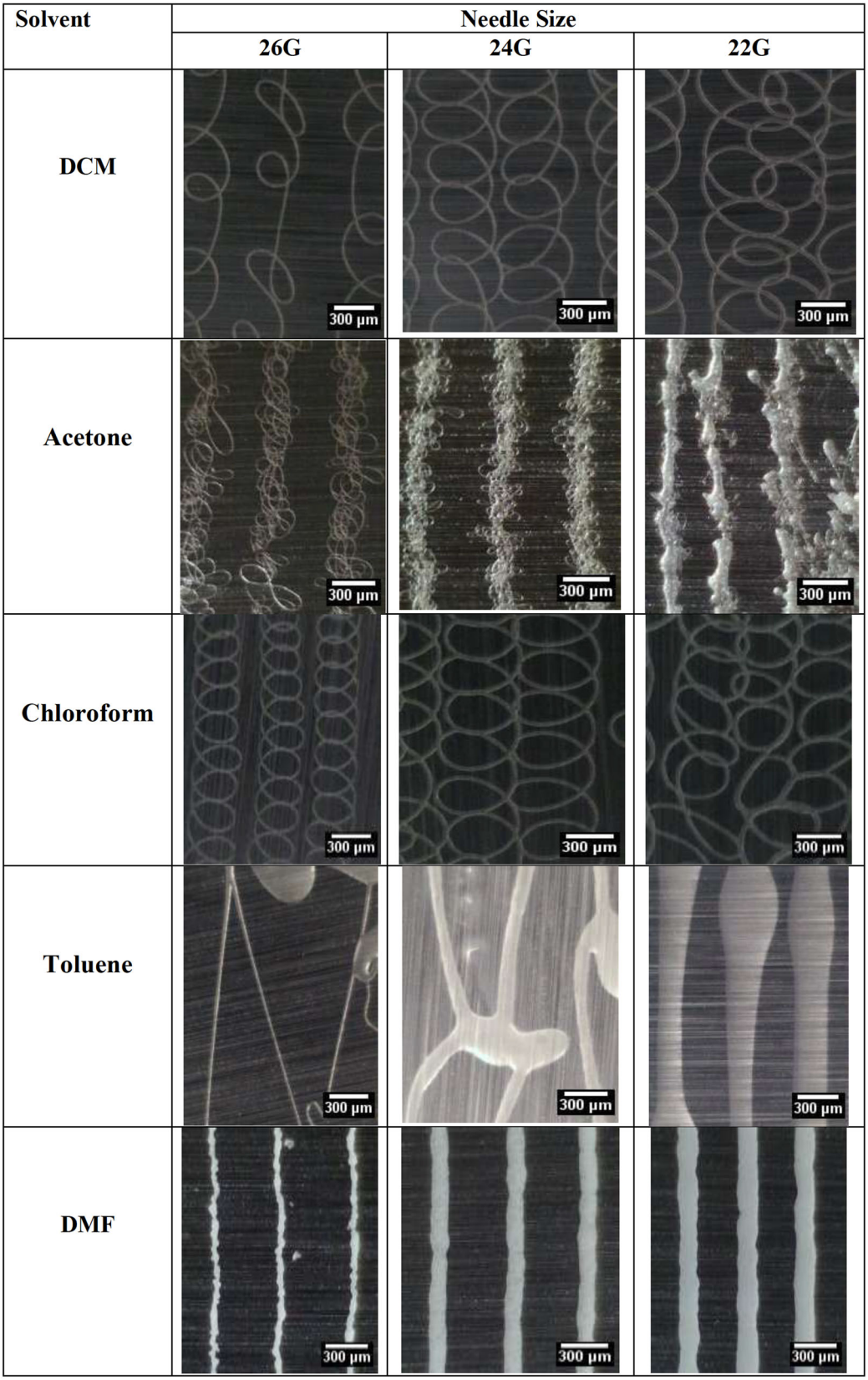


Figure 8. Examples of PCL fibres created when the SOD was 10 mm and the voltage was 4.2 kV.

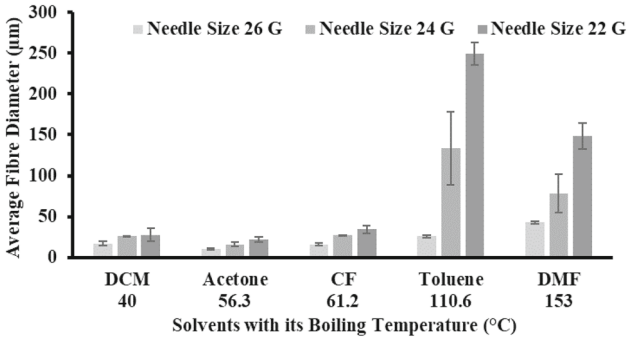


Figure 9. The effect of boiling temperature of five different solvents on fibre diameter with three different needle gauge size at SOD of 10 mm. Error bars represent the standard deviation in the data.

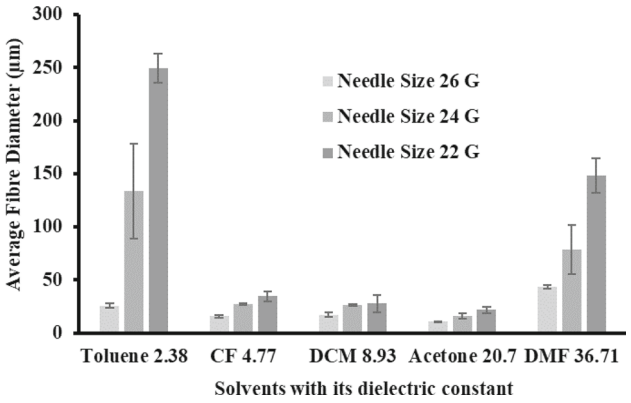


Figure 10. The effect of dielectric constant of five different solvents on the fibre diameter with three different needle gauge size at SOD of 10 mm. Error bars represent the standard deviation in the data.

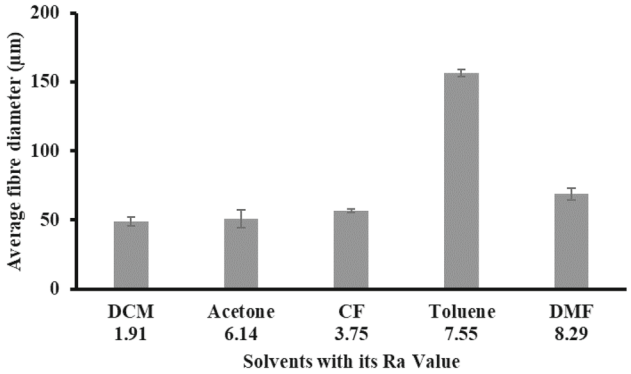
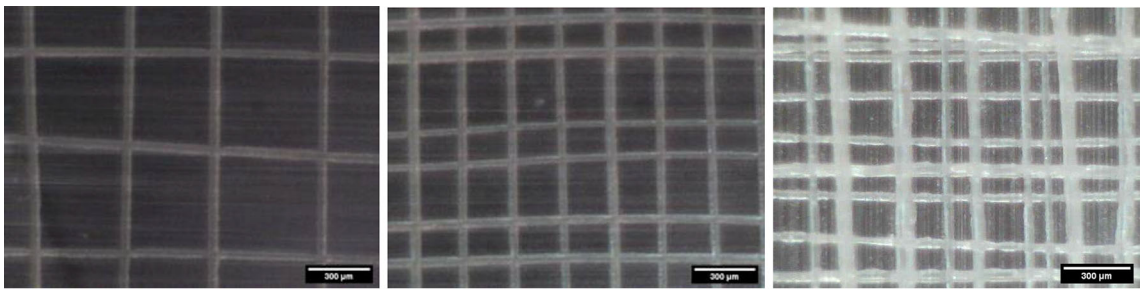


Figure 11. The relationship between average fibre diameter (μm) and Ra value of DCM, CF, acetone, toluene and DMF.

accumulated in the fibre causes whipping effect, which imparts stretching that leads to thin fibre. In spite of having high boiling temperature, acetone induces smaller diameter fibre because it has high dielectric constant that increases the repulsive force leading to more whipping and form thinner coil-shaped fibre. In case of higher boiling temperature solvents, toluene and DMF produced straight fibre but flattened on the substrate. The unexpected pattern was obtained from toluene because it has very low dielectric constant, which does not help stretching the fibre but at 10 mm SOD the fibre diameter was thinner compared to 3 and 5 mm. Even though DMF has high dielectric constant, it produces straight fibre with large fibre diameter. This is because, DMF has high boiling temperature and the solvent cannot evaporate completely before the deposition of jet on the substrate. Figures 9 and 10 show similar trends for the relationships between the fibre diameter and boiling

Table 3. Summary of average fibre diameter from different solvents at 3, 5 and 10 mm stand of distance with 26G, 24G and 22G needle gauge.

Solvent	Boiling temperature (°C)	SOD (mm)	Needle gauge size		
			26G/260 μm ID (μm ± SD)	24G/311 μm ID (μm ± SD)	22G/413 μm ID (μm ± SD)
DCM	40	3	*49.16 ± 3.38*	*86.33 ± 16.28*	*99.49 ± 27.2*
		5	23.89 ± 1.94	44.27 ± 3.47	51.23 ± 7.22
		10	17.1 ± 2.47	26.15 ± 0.54	27.74 ± 8.73
Acetone	56.3	3	*51.07 ± 6.45*	*109.22 ± 11.2*	*151.23 ± 30.11*
		5	17.23 ± 2.06	40.26 ± 1.77	36.44 ± 1.18
		10	10.36 ± 0.72	15.75 ± 2.81	21.66 ± 3
CF	61.2	3	*56.79 ± 1.39*	*137.88 ± 7.26*	*243.59 ± 28.89*
		5	22.44 ± 0.82	58.23 ± 2.93	113.47 ± 2.53
		10	15.76 ± 1.43	27.04 ± 0.66	34.43 ± 4.95
Toluene	110.6	3	*156.66 ± 2.41*	*245.77 ± 32.9*	*321.87 ± 48.64*
		5	*140.8 ± 1.23*	*197.25 ± 27.35*	*267.15 ± 18.2*
		10	25.69 ± 2.03	133.79 ± 44.68	*249.45 ± 13.69*
DMF	153	3	*68.99 ± 4.26*	*151.47 ± 17.49*	*225.86 ± 6.18*
		5	*52.95 ± 4.01*	*105.64 ± 4.19*	*174.13 ± 11*
		10	*43.12 ± 1.64*	*78.42 ± 23.47*	*148.37 ± 16.39*



(a) (b) (c)

Figure 12. The magnified images of (**a**) 2, (**b**) 4 and (**c**) 9 layers scaffold produced from DCM with 26G needle gauge at 3 mm SOD.

temperature and dielectric constant when comparing with the previous set of the results.

Table 3 presents a summary of the experimental results. The italic emphasis cells in the table indicate the conditions that straight fibres were obtained. All solvents could produce the straight fibres when the SOD was 3 mm, but the low boiling temperature solvents could not produce the straight fibres when the SOD was increased. DMF delivered the smallest straight fibres diameter when the SOD was 10 mm, and the 26G needle was used. However, the straight fibres obtained from DMF and toluene were not uniform. Therefore, DCM was recommended among the five solvents for a solvent used for creating a scaffold with a controllable pattern. In addition, the influence of solubility parameter, additional factor, has been investigated. The solubility parameter indicates the intimate interactions between the solvent and the polymer [32]. The Hansen Solubility parameters for PCL and five solvents were taken as a reference to calculate the Ra value. Ra value was calculated by using the following formula [45]:

$$\mathrm{Ra} = \sqrt{4(\delta D2 - \delta D1)^2 + (\delta P2 - \delta P1)^2 + (\delta H2 - \delta H1)^2} \quad (1)$$

Here, D, P and H represent dispersion force, polar force and hydrogen bonding components, respectively. According to Hansen Solubility theory, the lower the Ra value, the more solvents are compatible for the polymer. Figure 11 shows the relationships between the Ra value of five solvents and fibre diameter obtained at 3 mm SOD as we got smaller diameter from this SOD. The fibre experiences a rise in diameter with the increased Ra value except chloroform and DMF, and it seems that Ra values have less effect on fibre diameter compared to the boiling temperature of the solvent. Figure 12 presents the magnified images of two-layer, four-layer and nine-layer PCL scaffolds fabricated using a 26G needle and the SOD was maintained at 3 mm. The straight fibres were created, and the pattern could be achieved. However, the mechanical error of the machine caused the location error on the deposition.

5. Conclusions

Experiments were conducted successfully. The results showed that for NFES, both boiling temperature and dielectric property of a solvent influenced the straightness and diameter of the fibre. The influences, however, were opposite to FFES. A boiling temperature influenced the evaporation of a solvent. Having low boiling temperatures allowed DCM, acetone and chloroform to evaporate when they exposed to the environment quickly. Consequently, their fibres, despite a short flight time, could be formed before arriving at a collector. Dielectric constant influenced the amount of charge collected in a solution. Having high dielectric constants allowed the acetone and DMF to store more charge that provided more stretching force, but too much force created a whipping effect. The effect did not occur on the fibres from DMF, because DMF has a high boiling temperature. Among the five experimented solvents, DCM delivered the smallest uniform straight fibres. The scaffolds created from the solution with DCM showed promising results.

According to the findings, it is possible to achieve a smaller straight uniform fibre if a solvent has a boiling temperature near to chloroform or acetone to extend the solidification process, but have a low dielectric constant like toluene to avoid whipping effect. This solvent may be a mixture of two or more mutually soluble solvents, as experimented by Bain and Koomsap [29].

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