DESIGN, FABRICATION AND OPTIMIZATION OF COLLECTOR SET-UPS FOR OBTAINING ALIGNED NANOFIBERS

A Thesis submitted in partial fulfilment of requirements for the degree of

Bachelor of Technology

In

Biomedical Engineering

By:

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National Institute of Technology

Rourkela-769008

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Under the guidance of:

Prof. Bibhukalyan Prasad Nayak

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CERTIFICATE

This is to certify that the project entitled, **"Design, Fabrication and optimization of collector set-ups for obtaining aligned nanofibers"** submitted by **Raunaq Pradhan** is an authentic work carried out by him under my supervision and guidance for the partial fulfilment of the requirements for the award of **Bachelor of Technology (B. Tech) Degree** in **Biomedical Engineering** at **National Institute of Technology, Rourkela.**

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

Date:

Place: Rourkela

Prof./Dr. B. P. Nayak.
Dept. of Biotechnology & Medical Engineering
NIT Rourkela

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Raunaq Pradhan

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ABSTRACT

The objective of the electrospinning process is to obtain a fiber mesh or membrane which could be used as scaffolds in tissue engineering, wound healing, implant materials, drug delivery or medicinal materials. The fibers are formed on the collector plate due to the high potential electric field applied at the tip of needle which causes stretching of the polymer melt, in a spiral pathway and gets deposited on the collector plate. In conventional plate collector set-up, random nanofibers are deposited. However, aligned nanofibers are proved to be more useful for various specific purposes and difficult to obtain. Aligned nanofibres have found uses in skeletal tissue regeneration, neural cell seeding in scaffold, fuel cell electrolytes, electrochemical sensing, bone and blood vessel engineering, composite metal reinforcement and many other applications. The aim of this work is to alter the collector set-up designs to change the morphology of fibers obtained on the collector plate in an attempt to obtain aligned nanofibers. Briefly, ten different cost effective collector set-ups were fabricated. Electrospinning was performed using those collector plates and a polymer solution of Chloroform, Dichloromethane and Dimethyl formamide in 3:1 ratio was used. Other processing parameters such as applied voltage (12kV), feed rate (1mL/hr), tip collector distance (12 cm) were also optimized. The fibers obtained using the various collector setups were analysed using optical microscope and SEM. It was found that the alignment of the fibers obtained from the various collector set-ups varied with respect to each other. Best results were observed in case of grid shaped collector where the nanofibers were seen to be highly aligned. Alignment to a certain extent was also observed in case of static parallel electrodes collector set-up (ferrite magnetic strips) and in case of boat shaped collector for a small time period. This leaves us with the future prospect that the morphology of fibers can be further curtailed by modifying collector designs to obtain highly aligned nanofibers.

Keywords: Electrospinning, aligned, nanofiber, scaffold, collectors, collector design, SEM

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List of Abbreviations:

Abbreviated form:	Expanded form:
DCM	Dichloro methane
DMF	Dimethyl formamide
HFIP	Hexafluoro iso propanol
PAN	Poly acrylo nitrile
PCL	Poly-ε-caprolactone
PEO	Poly ethylene oxide
PLGA	Poly lactic-co-gylcolic acid
PVP	Poly vinl pyrrolidone
P-(LLA-CL)	Poly (L-Lactide-co- ε-caprolactone)
SEM	Scanning Electron Microscope
TFE	Tetra fluoro ethanol
THF	Tera hydro furan

Chapter-1

Introduction

Earlier, conventional processes like wet spinning, dry spinning **[1],** or melt spinning were used to create polymeric fibers which produced fibers ranging from 10 to 500 micrometre on application of very high pressure to a polymeric fluid. However, the process of **Electrospinning** involves application of a very high voltage, to create an electronically charged jet of polymer solution or melt, which upon drying or solidification produces a polymer fiber. An electric field is set up between the two electrodes, one holding the polymer solution inside a syringe and the other, the collector plate where the polymer fibers are deposited. When the electric field overhauls the surface tension of the droplet, a charged jet stream of polymer solution is ejected from the jet which exhibits bending instabilities due to repulsive forces between the charges carried with the jet. The jet extends through spiraling loops, as the diameter of the loops increase the jet growing longer before solidifying on the collector resulting in formation of a nanofiber **[2].**

The first patent for electrospinning setup was issued to Formhals in the year 1934 (US patent 1-975-504) **[3].** In the past several decades, this technique has been used to create fibers from a wide range of polymers including biopolymers, engineering plastics, ceramics, polymeric materials, conducting polymers, and polymer blends. The morphology of fibers obtained can be monitored by making structural changes in the design of collector plate or various process related parameters.

Alignment of fibers which is the main objective of my study has found considerable uses in skeletal tissue regeneration, neural cell seeding in scaffold, fuel cell electrolytes, electrochemical sensing, bone and blood vessel engineering, composite metal reinforcement and many other applications. **[8]**

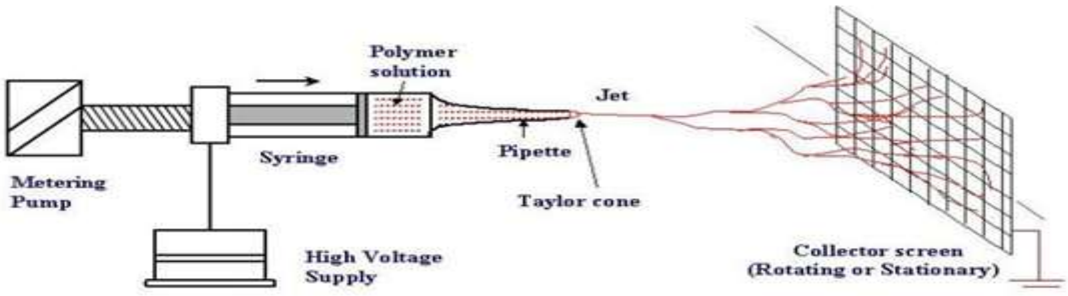


Figure 1.1 **Schematic of an Electrospinning setup**

Basically the process of electrospinning can be explained in five steps:

1. Charging of the polymer fluid
2. Formation of the Taylor cone
3. Thinning of the jet (in presence of electric field)
4. Instability of the jet
5. Collection the fibers on the collector plate

1.1.1 Charging of the polymer fluid

The polymer solution is filled inside the syringe which is charged to a very high potential, usually around 10 KV, by means of a high potential electrode known as induction charging. An electrical double layer is formed where ion or ion pairs are generated as charge carriers based on the polarity of the solution. For non-conducting fluid charges are introduced by applying an electrostatic field.

1.1.2 Taylor cone Formation

Based on the applied voltage, the similar charges in the electrical double layer repel and act against the surface tension of the fluid to deform it into a cone shaped structure known as Taylor cone. Beyond a certain potential, the Taylor cone becomes unstable and the jet is emitted from the tip of the cone. **[4]**

1.1.3 Formation of a thin jet

The charged fluid gets accelerated in the presence of an electric field and forms a thin stream of fluid. This region is usually linear.

1.1.4 Instability of the jet stream

The fluid is accelerated in the presence of an electric field and due to one or more bending instabilities follows a spiral and distorted path before getting deposited on the collector plate**. [5]**

1.1.5 Collection of fibers on the collector plate

The charged fluid gets deposited on the collector plate which is usually held at a lower potential. The morphology of fibers obtained can be varied depending on the design of the collector plates.

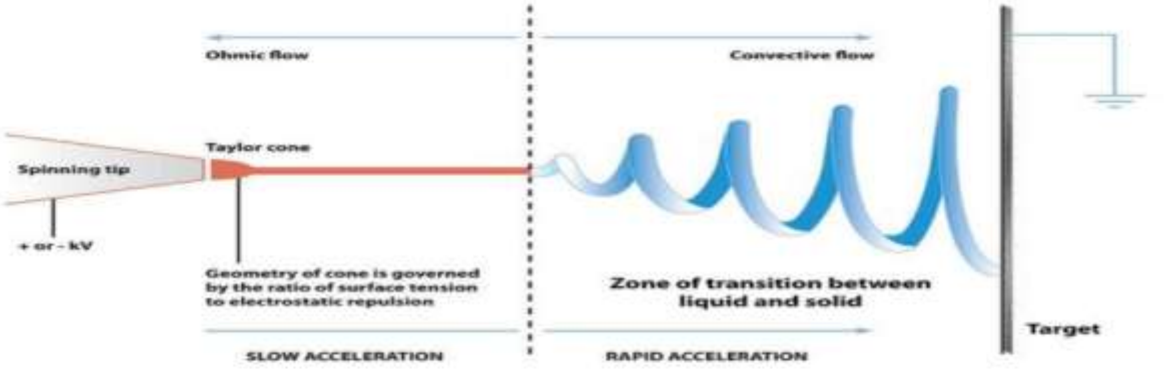


Figure 1.2 Schematic diagram of an Electrospinning process

The electrospinning process is affected by various parameters. Broadly, it can be classified into three different categories:

1. **Solution related parameters**
    a. Molecular weight and solution viscosity
    b. Surface Tension
    c. Solution conductivity
    d. Dielectric constant of the solvent
    e. Volatility of solvent

2. **Process related parameters**
    a. Applied electric potential
    b. Feed rate of the solvent
    c. Diameter of orifice of needle
    d. Effect of collector plate
    e. Distance between tip and collector

3. **Environmental parameters**
    a. Temperature
    b. Humidity
    c. Air Velocity in chamber

1.2 Objectives

The present work mainly focuses on modification of various collector setup designs in an attempt to obtain aligned nanofibers by cost effective methods. The detailed objectives are outlined below:

- Designing of various collector set-ups.
- Preparation of polymer solution for the process of electrospinning.
- Collection of fiber on the collector plate after electrospinning.
- Analysis of the fibers obtained by the various collector set-ups.

Chapter-2

Literature Review

2.1 Advantages of Electrospinning

The process of electrospinning had several advantages as compared to other methods such as self-assembly, drawing, phase separation etc. for producing continuous nanofibers ranging from 10 to 100 µm. **[6]** Various processing parameters were modified in an attempt to obtain better fibers. It has been reported that 4% wt. concentration PEO had the highest viscosity and lowest beads as compared to 1% wt. concentration PEO. It has been reported that increase in application of electric potentials lead to the fibers becoming more rougher. It has also been reported that over the years, electrospun polymer nanofibers have found extensive use in composite reinforcement, tissue template, filtration systems and medical prosthesis mainly grafts and vessels.

2.2 Fiber formation by air gap electrospinning process

3-D nerve fibers were fabricated using the air-gap electrospinning process**[7]** where poly-e-caprolactone (PCL), dissolved in Tetra fluoro ethanol (TFE) at various concentrations, was used as the polymer solution due to its slow rate of degradation. The system consisted of two vertical piers grounded to a common voltage (-4 kV to -16kV). The solution was charged to +22kV and feed rate was kept at 2-20 ml/hr. The distance to collector tip was varied between 10cm-30 cm. It has been reported that the polymer solution is stretched back and forth in a series of loops, resulting in formation of parallel nanofiber aligned arrays. These have found extensive use in peripheral nerve tissues and nerve injuries.

2.3 Fiber formation by using non- conducting plexi glass disks

Alignment of polymeric nanofibers was produced by using two circular plexi-glass disks**[8],** non-conducting in nature with a diameter of 12.7 cm and had 6mm cuts around the circumference at a distance of 1 cm apart. The disks were placed 30 cm apart on top of a rod. The copper wire was grounded.20 gm of nylon beads mixed in 50 gm of formic acid was dissolved to form a uniform mixture. The polymer solution was put inside the syringe and feed rate was kept at 5 μL/min, applied potential being 20kV. Fibers were obtained after 5 min while the drum was being rotated at 1 rpm. The fibers experienced two sets of forces – one due to electrostatic potential difference and the other due to the incoming charged fiber and the charge on its surface. When a particular needle comes close to it, the fiber is attracted, but then the drum is rotating. So the fiber attaches to the next wire, however due to the charge on the previous wire, the fiber is stretched and spans across the gap in a perpendicular direction resulting in alignment of fibers obtained. It has been reported that the aligned mats are thick to handle and cut after 15 mins.

2.4 Fiber formation by using non-conductive ferrite magnets

Aligned electrospun nanofibers were also produced by usage of two non-conductive ferrite magnetic strips placed at some distance as collector plates for deposition of fibers **[9]**. It involved usage of a polymeric solution which did not have magnetic nanoparticles. Polyethylene oxide was used to prepare a solution of 4 wt% (ethanol:water= 2:3). Ferrite magnetic strips of strength 12T were used and 7.5 kV electrical potential was applied. The tip collector distance was kept at 20cm and experiments were performed at room temp (25 ˚C). It was reported by SEM analysis that PEO fibers were uniaxially aligned across the ferrite gap along the longitudinal axes. The alignment was found to be quite good in this case. It was also reported that the aligned fibers had potential applications in fiber reinforcement or tissue engineering.

2.5 Fiber formation by using Si doped metal

Aligned nanofibers were produced using a collector set up which had two electrically conducting metal plates (metals or metals with silicon doped in it) **[10],** placed at some distance from each other with a gap in between. The width could be varied from micrometres to centimetres depending on the requirement. Here, two types of polymer solutions were tried out- i.e. polyvinyl pyrrolidone (PVP) and polyacrylonitrile (PAN). The flow rate was kept as 0.2 mL/h and 0.3 mL/h and the tip collector distance was 7.6 cm and 14 cm respectively. An electric voltage of 5 kV was applied in both the cases. It was reported that the charged jet experiences two forces: one from the splitting electric field and the other due to induced surfaced charges on the two grounded electrodes. The fibers present closest to the electrodes stretch across the gap to form aligned nanofibers. It has also been reported that variety of other materials such as ceramics, composite materials, organic functional molecules, nanoparticles, bio-molecules could be used to generate aligned nanofibers with desired functionalities. It is being believed that this method could be used for functional materials as well where anisotropic alignment of active components could lead to exciting new features and applications.

2.6 Fiber formation by using rotating disc collector

Aligned nano-fibers were obtained by using a rotating disc as the collector **[11]** with the tip collector distance being 200mm. The aluminium disc has a tapered edge all over it to create a stronger electric field. A potential difference of 8kV was applied and the experiments being performed at room temperature. A 3% weight concentration of PEO was used with ethanol: water ratio being 2:3. During the process, the disc was rotated at a linear speed of v=5.3 m/s as the fibers were collected on the edge, which was wound round the wheel. An aluminium table was rotated around the Z-axis attached to the disk to collect nanofibers at every 10s. The angle was set again for the next fiber to be collected by momentarily stopping the collector disk. It has been reported that the diameter of the fibers obtained was not uniform ranging from 10-180 nm but a high degree of alignment was seen.

2.7 Fiber formation by using Tip Collector

Aligned nanofibers can also be produced by using a tip collector **[12].** The set up consisted of an assembled collector, containing a grounded wire electrode and an electrode holder which contained a wooden board (length-38cm) and insulating paint covered metal frame (length-63 cm). 5-12% (w/v) Poly caprolactone(PCL) in mixture of 1:1 THF, DMF and 7-15% (w/v) poly acrylonitrile(PAN) in DMF was used in the polymer solution for the process of electrospinning. The tip collector distance was roughly 25 cm and the applied electrical potential was 12kV. It has been reported that aligned nanofibers were obtained after 4 hrs in the wooden board collector and after 7 hrs in the insulating metal frame holder. It has also been reported that uniformity of fibers increased with increase in spinning time.

2.8 Fiber formation by horizontal placement of magnets on an Al foil followed by plasma treatment

Aligned nanofibers can also be produced by using a collector set up where two magnets were placed horizontally on an aluminium foil and plasma treatment was done on the obtained fibers **[13].** 10 wt % concentration Poly vinyl pyrrolidone (PVP) dissolved in ethanol was used as the polymer solution. Ferric oxide nanoparticles 250 nm diameter were dispersed in the PVP solution at a mass ratio of 3:1for 24 h. The feed rate was set to be 2 mL/hr and a 15kV voltage was applied. The obtained fibers were passed through plasma cleaner at 0.1 MPa and 100W to remove the organic materials. Its analysis by SEM provided aligned magnetic ferrite nanofibers.

2.9 Fiber formation by using rotating mandrel: PLGA in HFIP as polymer solution

Aligned polymeric nanofibers were produced by using a rotating mandrel, 11 cm in length and 3.5 cm in diameter with an earthed collector plate **[14].** 20% (w/v) PLGA dissolved in HFIP was used as the polymer solution. The tip collector distance was fixed at 15 cm and an a voltage of 25 kV was applied. The feed rate was set to be 1ml/hr. It has been reported that if the mondrel was rotated at 300 rpm, it produced random fibers whereas increase in speed upto 1500 rpm, produced aligned nanofibers. It has been reported that thin sheets with diameter ranging from 0.1-0.3mm were produced.

2.10 Fiber formation using a rotating drum collector: P-LLA-CL in HFIP

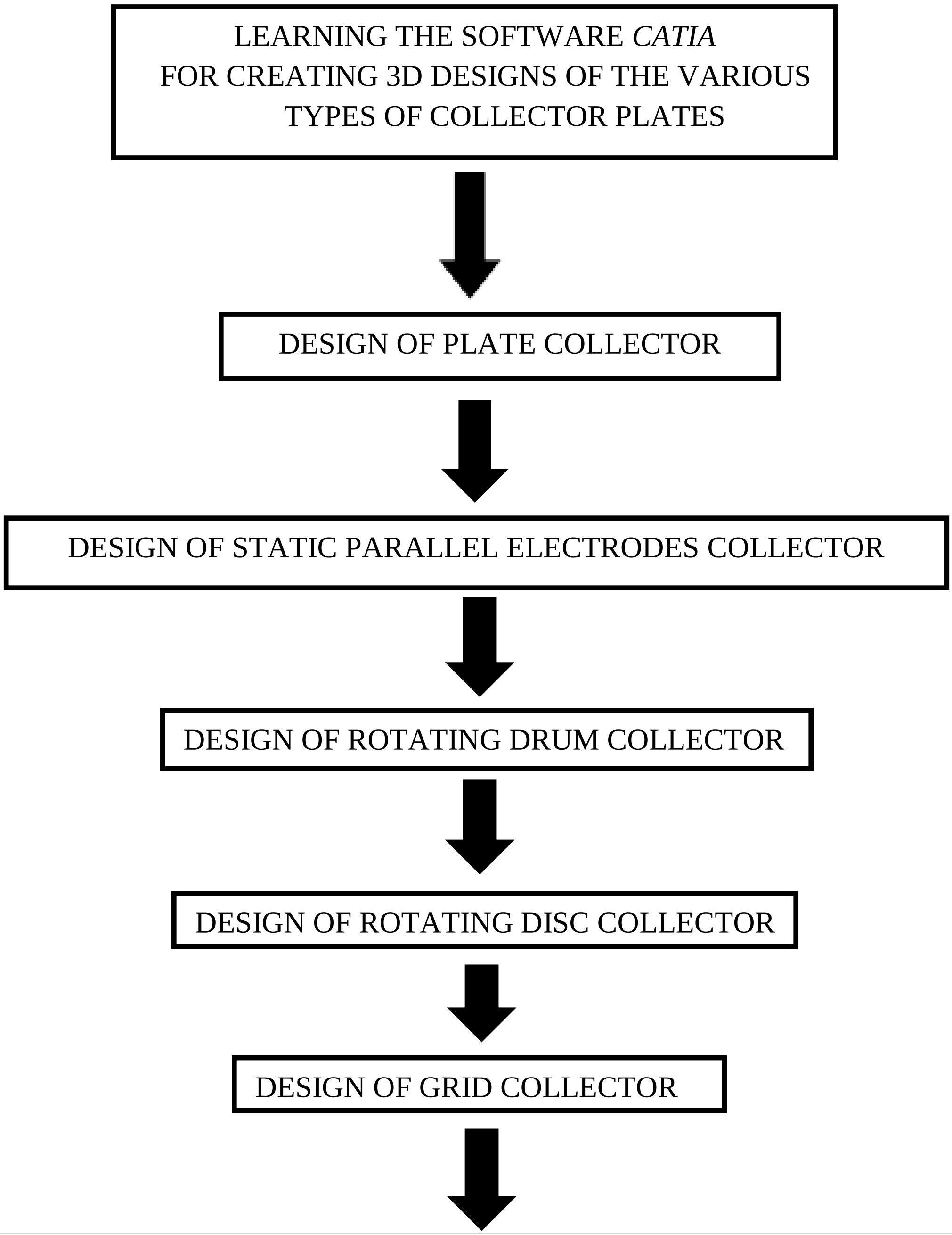
Aligned nanofibers were produced by using a rotating drum collector **[15]**. In this set-up, 4% (w/v) P(LLA-CL) was dissolved in HFIP and stirred at room temperature. The prepared solution was used as the polymer solution. The feed rate was set to be 1.2 mL/h and a voltage of 12 kV was applied across the needle. The tip collector distance was varied from 12-15 cm for optimum results. It has been reported that the drum was rotated at a speed of 4000 rpm for obtaining aligned nanofibers. It was observed that at low rotational speeds, random fibers were obtained and at very high rotational speed, fibers were not aligned. Linear rate of the rotating drum should match with the evaporation rate of the solvent, such that the fibers are deposited and taken up on the surface of the collector.

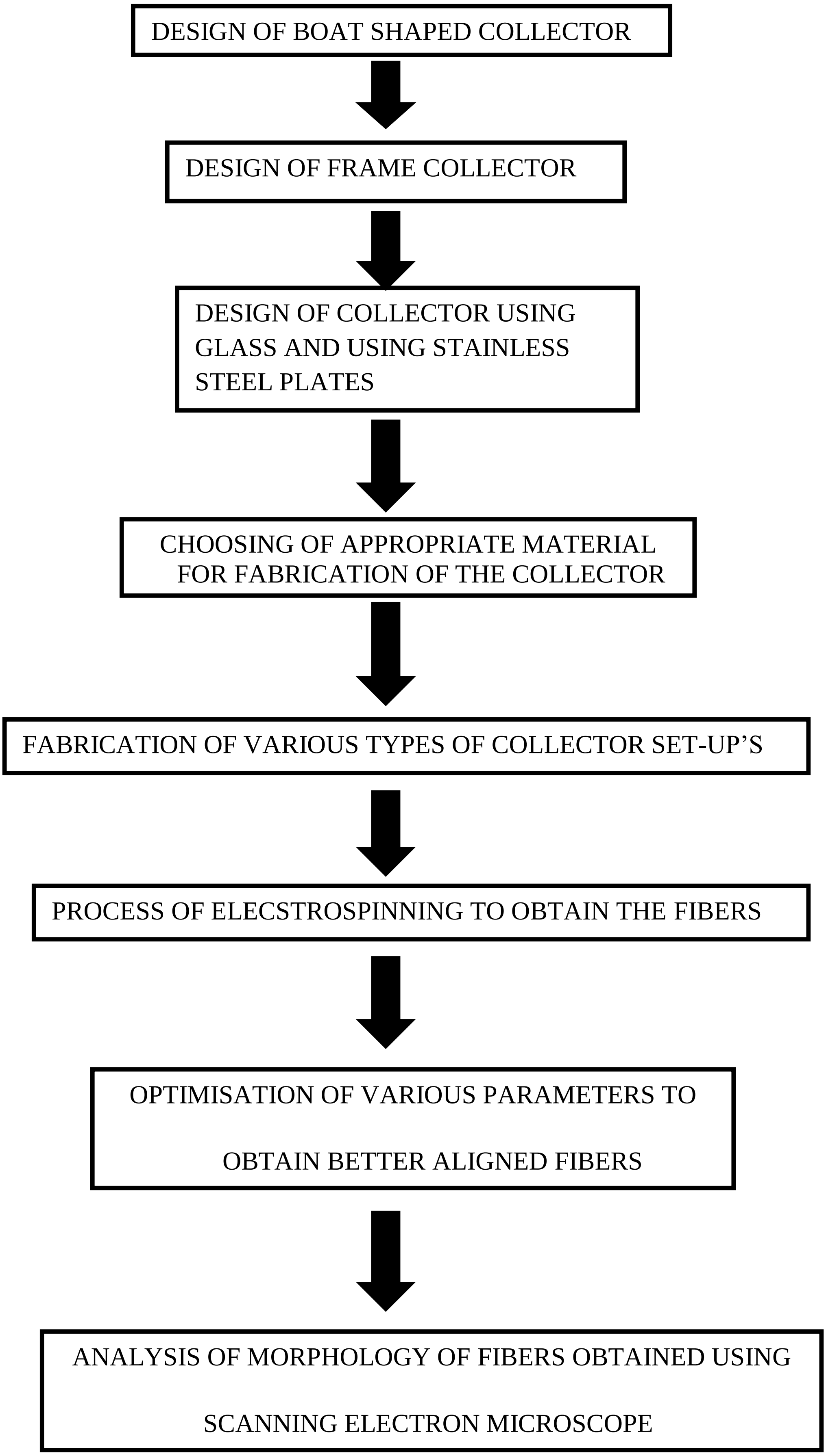
Chapter-3

Materials and Methods

3.1 Plan of Work:

Various collector set up's were designed using CATIA and then was fabricated using cost effective materials. The following flow chart denotes the work methodology in the current project which involves creation of aligned nanofibers.




DESIGN OF BOAT SHAPED COLLECTOR
DESIGN OF FRAME COLLECTOR
DESIGN OF COLLECTOR USING GLASS AND USING STAINLESS STEEL PLATES
CHOOSING OF APPROPRIATE MATERIAL FOR FABRICATION OF THE COLLECTOR
FABRICATION OF VARIOUS TYPES OF COLLECTOR SET-UP’S
PROCESS OF ELECSTROSPINNING TO OBTAIN THE FIBERS
OPTIMISATION OF VARIOUS PARAMETERS TO OBTAIN BETTER ALIGNED FIBERS
ANALYSIS OF MORPHOLOGY OF FIBERS OBTAINED USING SCANNING ELECTRON MICROSCOPE

3.2. Design of various collector set-ups

In an attempt to obtain better aligned fibers, different type of collector designs were tried out which were cost effective in nature and the effect on fiber morphology was observed for each case. The syringe containing the polymer solution is connected to a very high voltage (cathode) and the other terminal anode is grounded or connected to the collector plate. The various types of collector designs tried out are mentioned below:

3.2.1 Collector design – 1

A simple **plate collector** is designed in which a rectangular shaped aluminium plate with dimension 30 cm x 12 cm. The figure on the extreme left in the first row denotes the FRONT view, the figure below it denotes the TOP view and the figure on the right in the first row denotes the SIDE view. The random fibers collected on the surface of the plate collector are used as reference to compare with the aligned nanofibers.

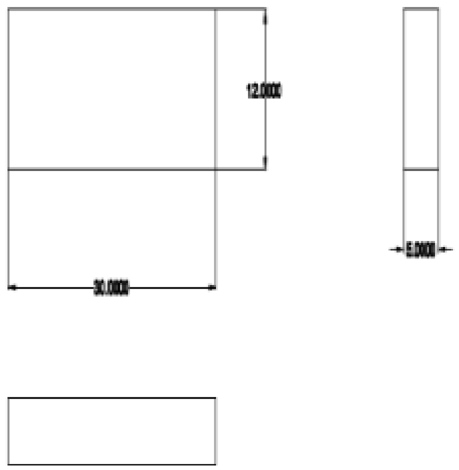


Figure-3.1 Design of a plate collector

3.2.2 Collector design-2

It consists of two ferrite magnets having dimensions of 10cm x 2cm with a thickness of 2cms placed at a distance of 3 to 5cms from each other on a conducting plate. The fibers are collected between the two magnets, due to the interaction of magnetic and electric field, fibers spinning back to and fro between the magnets.

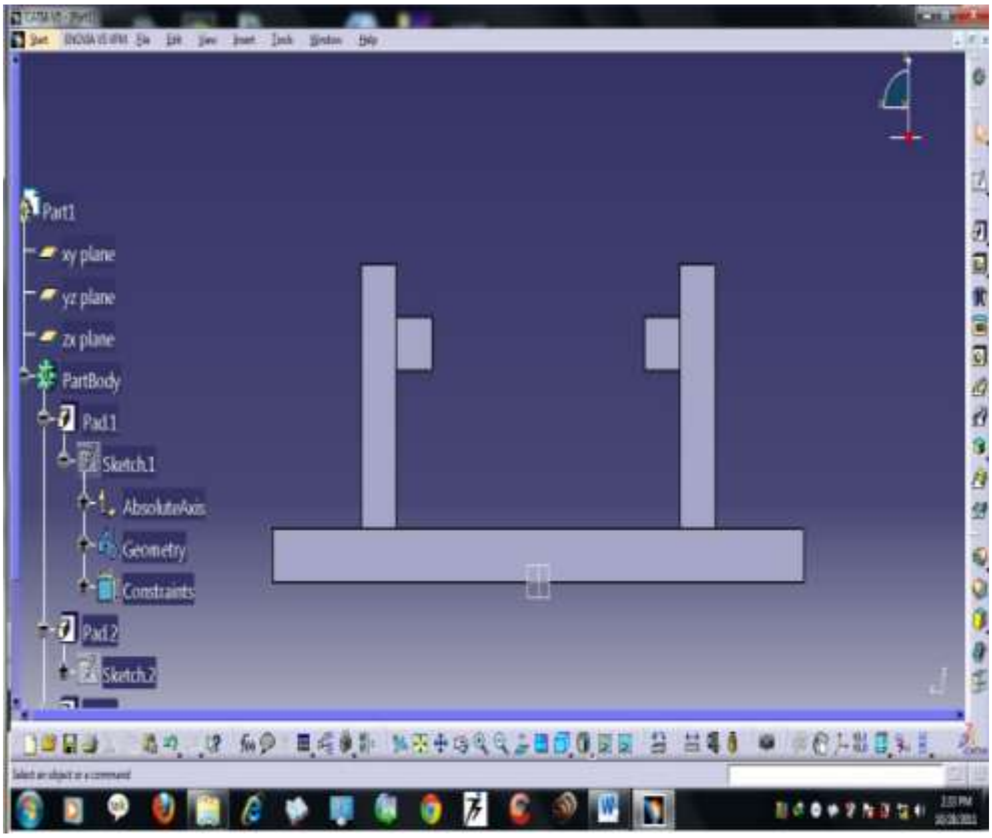


Figure 3.2 Design of a static parallel electrodes collector

3.2.3 Collector design-3

A rotating drum is designed as the collector plate for collection of fibers. Here, the length of the drum is 30cm; the internal and external diameter of the drum being 2 cm and 6 cm respectively. The length of shaft is 40 cm and diameter is 6 cm. The fibers are stretched across the surface when it is rotated at high speed and get aligned on the collector due to the interacting electric fields.

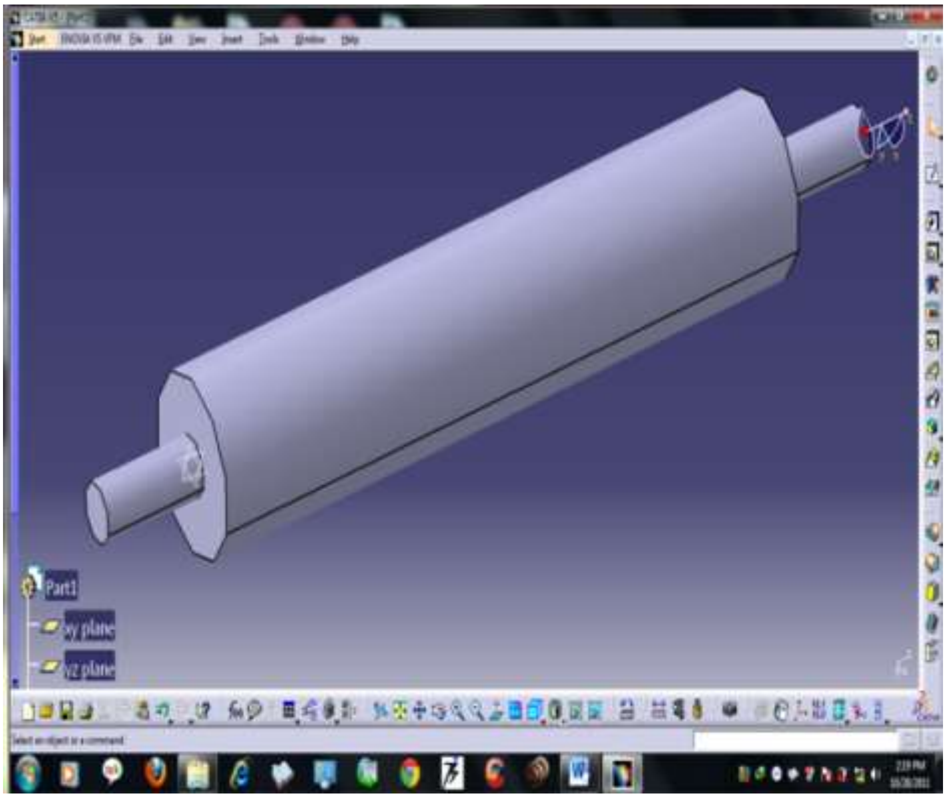


Figure 3.3 Design of a rotating drum collector

3.2.4 Collector Design-4

A circular disc with a diameter of 30 cm is used as the collector in this case. It has an edge all over it with a thickness of 2 cm all over it. The disc is rotated which creates an electric field and the fibers are attracted towards the edge. High rotational speed provided better aligned fibers. If the rotational speed is too low, then the fibers formed are discontinuous and proper fiber formation does not take place. If the speed is too high, fibers may not be formed properly. So, the speed should be optimum. The fibers are collected on the edge over the disc which is connected to a table where the fibers are deposited and the rotation is stopped momentarily to cut and separate the fibers before the disc starts rotating again.

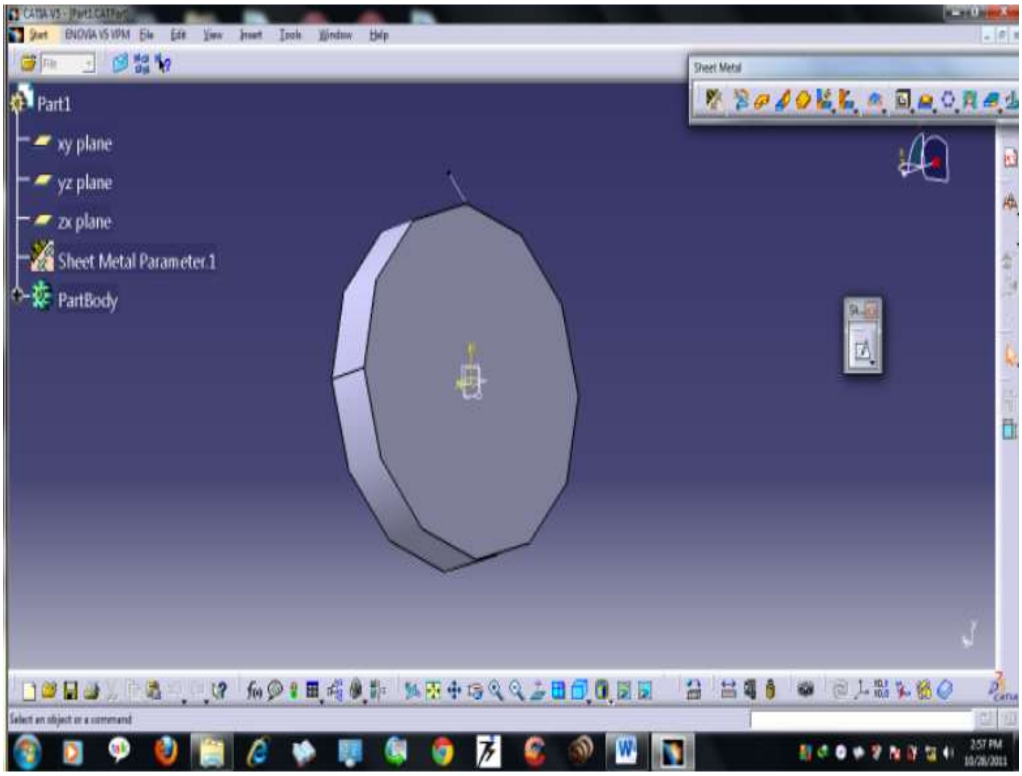


Figure 3.4 Design of a rotating disc collector

3.2.5 Collector design-5

This collector design is normally termed as **frame collector.** In this set-up, a plate collector which consists of a conducting material has an aluminium foil placed over it. A frame consisting of a wooden rectangular disc is wrapped with aluminium foil with lines in it where the fiber gets collected and placed at a certain angle with the plate collector (60˚ in this case). The frame may consist of other material as well. When the fibers come down in form of a spiral path, they have the tendency to go in different directions, and so during that period, it gets deposited on the frame collector. This angle at which it is placed can be varied for obtaining better alignment of fibers. The fibers are collected on the straight lines present in the aluminium foil in the frame collector.

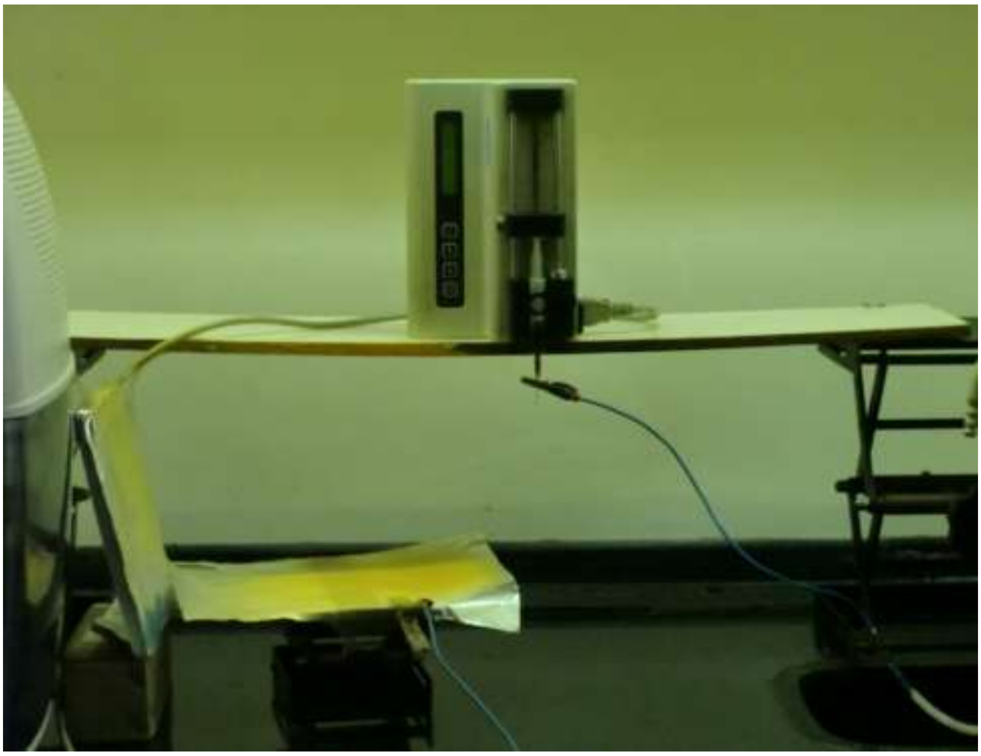


Figure 3.5 Design of an aluminium frame collector

3.2.6 Collector design-6

This collector set-up consists of a 3 x 3 copper wire grid supported by copper wires on its four ends. The grid spacing between the copper wires is kept at 2 cm. The fibers are deposited on the surface of the grid as well as between the horizontal and vertical lines of the grid due to the interaction of the electric field by the copper wires where fiber is stretched between 2 wires in aligned manner.

When fiber gets attached to one wire, it is attracted by the other copper wire to get strectehd and aligns itself. Four horizontal supports constructed of thermocol are placed around the grid collector and the whole set-up is covered by a plastic cellophane paper which prevents the air velocity from affecting the fiber formation process.

Figure 3.6 Design of a grid collector

3.2.7 Collector design-7

It consists of an aluminium sheet which has been bent in the form of a U-shaped boat structure. Here, the fibers are collected between the two ends of the structure. The fibers fall on one end of the structure and are attracted by the other end due to electric field interaction between the two: as a result fibers could be stretched across the two ends resulting in an aligned fibers.

Figure 3.7 Boat shaped collector

3.2.8 Collector design-8

It consists of two glass plates 5mm width covered with aluminium foil and placed over a conducting plate. Fibers obtained on the surface of the plate are random. Alignment to some extent was seen between the two glass plates where fiber was stretched due to electric field interaction between the plates.

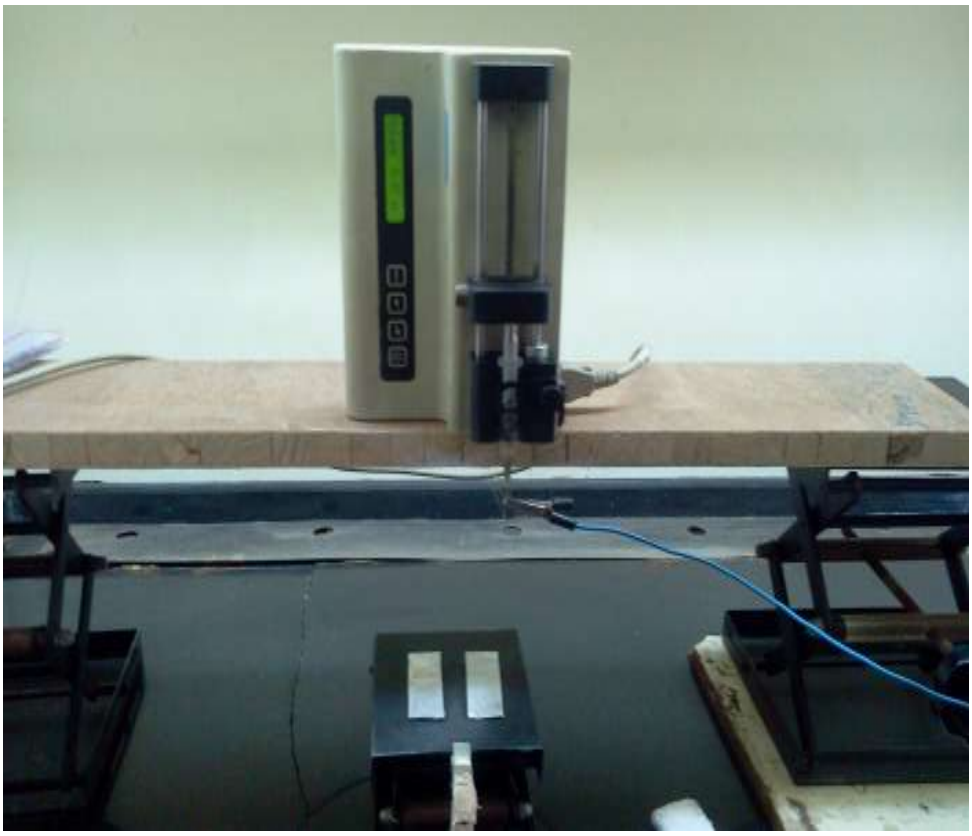


Figure 3.8 Glass plates covered with Al placed on a conducting substrate

3.2.9 Collector design-9

It consists of two glass plates 5mm width covered with aluminium foil placed on a non-conducting surface (i.e. card board box). Fiber collected on plate surface was random. Alignment could be expected in fibers stretched between the two glass plates but lesser alignment was seen in the thin sheet of stretched fiber across plates as compared to when placed on a conducting base.

Figure 3.9 Glass plates covered with Al placed on a non-conducting substrate

3.2.10 Collector design-10

It consists of two stainless steel plates having width 4 cm and length 8 cm as collector plates which are placed 2cm apart. Very thin fibers are collected in the space between the two plates well as on the plates due to the electric field interaction of plates and applied field. Fibers obtained on the surface of the steel plates were random, however some alignment was observed along the plates thickness**.**

Figure 3.10 Two conducting Al plates placed on a non-conducting substrate

3.3 Other Optimized processing parameters

During the process of fiber formation in electrospinning, there are various processing parameters such as solution concentration, flow rate, applied voltage, tip collector distance etc. which play a very important role in the formation of fibers. These parameters have to be optimized in order to obtain better aligned nanofibers.

Different processing parameters were analysed with a plate collector and from among many alternatives, the most optimum parameters were chosen for alignment. The same parameters as mentioned below were used for all collector designs described above.

3.3.1 Type of solvent

Four different solvent compositions were used:

Solvent	Ratio	Remarks
$CHCl_3$:CH_3OH	3:1	
$CHCl_3$ + DCM: CH_3OH	3:1	
$CHCl_3$ + DCM: DMF	**3:1**	**Most optimum**
DCM: DMF	3:1	

Table 3.1 Type of solvents used for electrospinning

3.3.2 Polymer Solution concentration

Three different weight concentrations were used:

Weight %	Remarks
8	
10	**Most optimum**
12	

Table 3.2 Polymer solution concentration

3.3.3 Flow Rate of the solution

Two different flow rates were used:

Flow rate (mL/hr)	Remarks
1	**Most optimum**
1.5	

Table 3.3 Flow rate of the solution

3.3.4 Voltage applied

Three different voltages were applied to the solution:

Applied voltage (kV)	Remarks
10	
12	**Most optimum**
14	

Table 3.4 Applied voltage

3.3.5 Tip to collector distance

Four different combinations of tip to collector distance were tried out.

Tip collector distance (cm)	Remarks
8	
10	
12	**Most optimum**
15	

Table 3.5 tip to collector distance

3.3.6 Diameter of the needle of the syringe

The diameter of the needle used was **22G.**

So, the various ***optimized parameters*** used during the electrospinning process with the various collector set-ups described above are:

Process Parameter	Optimized values
Type of solvent used	**$CHCl_3$ + DCM: DMF (3:1 ratio)**
Polymer solution concentration	**10 wt%**
Flow rate	**1 mL/hr**
Applied voltage	**12 kV**
Tip to collector distance	**12 cm**
Diameter of needle	**22G**

Table 3.6 Optimized parameters for the electrospinning process

Chapter-4

Results and Discussion

4.1 Optimized Parameters:

The electrospinning process was performed using the various collector set-ups (collector set-up 1 to collector set-up 10) as mentioned in the previous chapter **3.1**.

Optimization of the various processing parameters for electrospinning was also done, the results of which were listed in **Table 3.6** and are also listed below.

Process parameter	Optimized values
Type of solvent used	**$CHCl_3$ + DCM: DMF (3:1 ratio)**
Polymer solution concentration	**10 wt%**
Flow rate	**1 mL/hr**
Applied voltage	**12 kV**
Tip to collector distance	**12 cm**
Diameter of needle	**22G**

4.2 Morphology Analysis:

Using the above processing parameters, electrospinning was done and the fibers were obtained on the various collector setups. In some cases, the fiber was not thick enough to be cut and analysed using SEM and optical microscope. There was no discontinuity of fibers. The diameter of the fiber was optimized to a large extent.

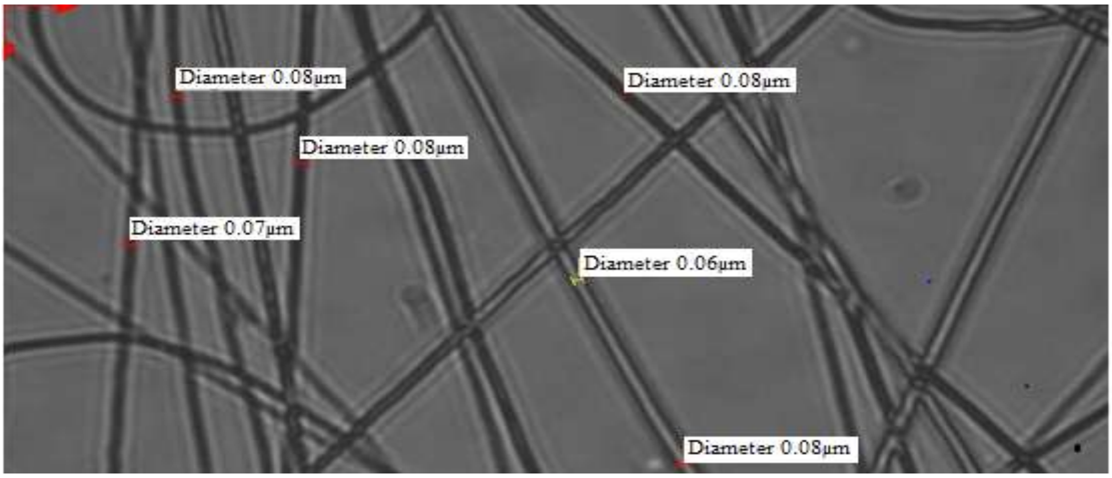


Figure 4.1 Optimization of fiber diameter

In case of plate collector, the electrospinning process is carried out till a thick sheet of fiber is deposited on the surface of the collector. It is then analysed using a Scanning Electron Microscope (SEM) and it was found that the morphology of the fibers obtained was very random. A thick sheet of non-aligned fiber mesh was deposited on the surface of the collector which had no particular alignment.

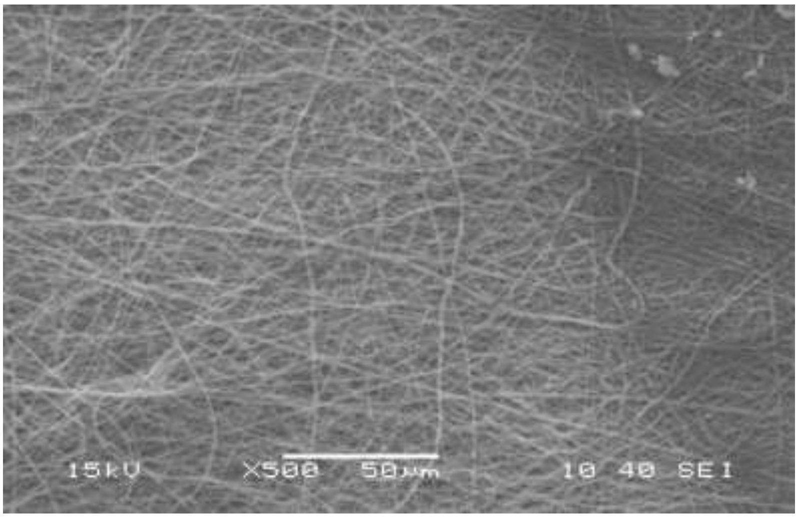


Figure 4.2 Random fibers mesh obtained in case of plate collector

In case of boat shaped collector, the fibers obtained between the two ends of the boat shaped structure was very thin. Its morphology was also found to be very random in nature. Initially, some sort of alignment was found for a very less amount of time when the fiber was very thin, and with increase in time, the alignment of fiber became random in nature.

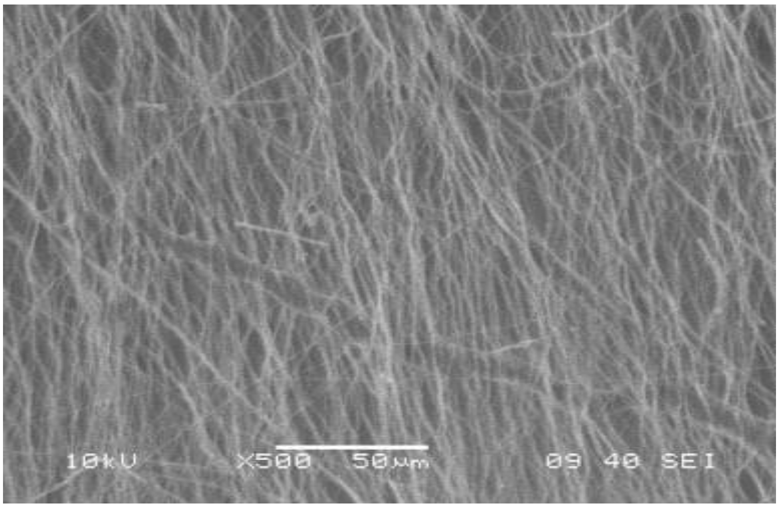


Figure 4.3 random alignment of fibers in case of boat shaped collector

In case of grid collector, the fibers were collected on the surface of the grid as well as between the grid spacings, horizontally and vertically. When analysed using SEM, good alignment of fibers was observed in the thick sheet of fiber deposited on the collector surface.

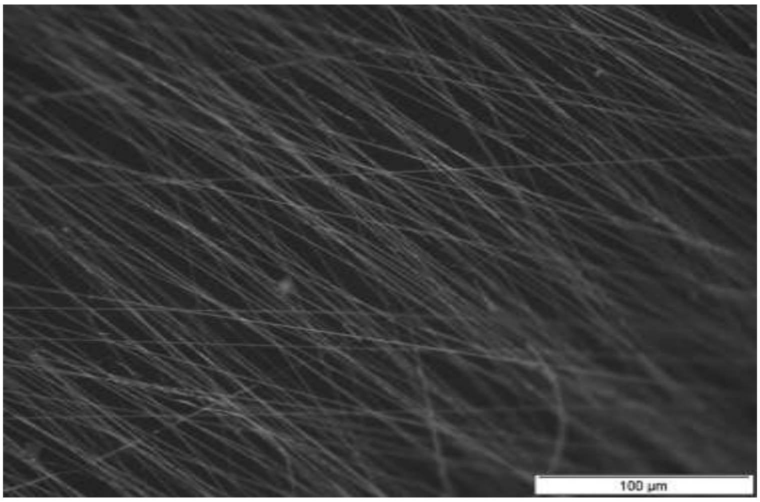


Figure 4.4 Alignment of fiber seen in case of grid shaped collector

In case of static parallel electrodes collector model which used two ferrite magnets placed at some distance from each other, the fibers are collected between the two magnets in such a way that a thin sheet of fiber is suspended in between, attached to both the magnets weakly. The morphology of fibers obtained in this case was found to be aligned to a certain extent with greater distance between two fibers as compared to grid shaped collector.

Figure 4.5 Alignment to a certain extent in case of fibers obtained by two ferrite magnets placed 5 cm apart

In case of frame collector, thin sheet of fiber was deposited on the surface of the frame. Alignment was observed in the initial stages of fiber formation, then after some time, it became random.

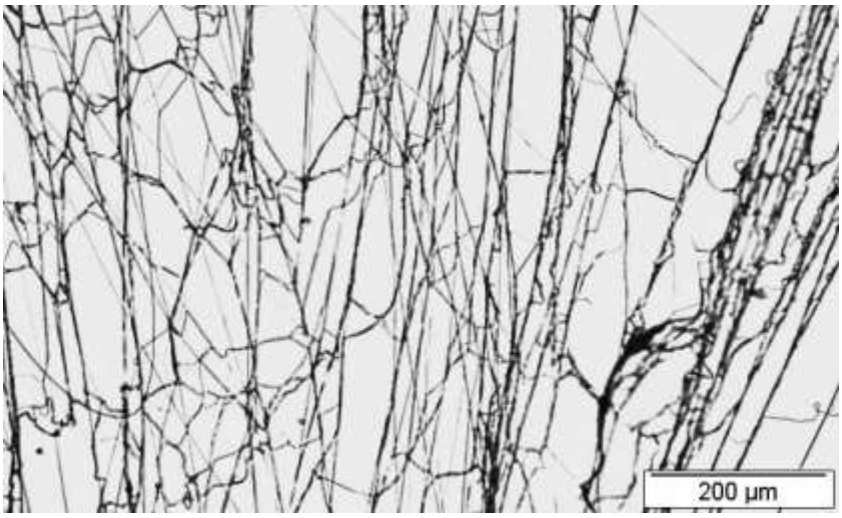


Figure 4.6 Initial alignment of fibers in case of frame collector

In case of glass strips covered with Aluminium foils placed either over a conducting or non-conducting substrate, and also in case of two stainless steel plates kept 2 cm apart. Some alignment was observed in case of the thin sheet of fiber stretched between the two surfaces along its thickness, more in case of conducting base as compared to non-conducting base. Due to the extremely low thickness of the glass plates, fiber obtained was very thin and not possible to cut for SEM analysis. Also, the field created due to the plates, being not very strong, less amount of fiber was obtained on the surface of the plates, most of them being random.

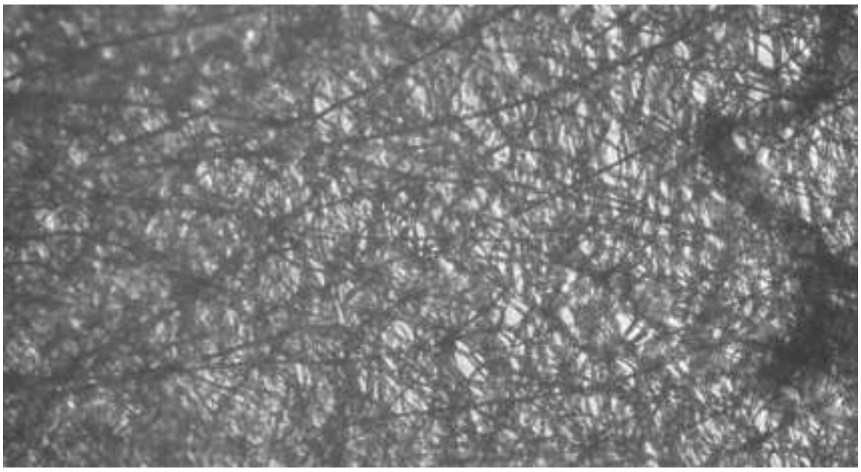


Figure 4.7 Random fibers obtained on surface of glass plates

Chapter-5

Conclusion &

Future scope

The various collector set ups designed in the present study were very cost effective and were easy to fabricate. All of them were designed in house using the materials available here. Some of them produced random fibers while alignment of fibers was seen in other cases. In some cases, the fibers were too thin to obtain a sheet and analyse them.

From the various set-ups which were fabricated on which aligned nanofibers were obtained, the best result was seen in case of **grid shaped collector** where high ordered alignment of fibers were observed. In the present work, only one type of grid was taken. This design can further be extended where different kinds of grid could be taken and the grid spacing could be changed to analyse its effect on fiber morphology.

The second best result was obtained in case of two ferrite magnets placed at some distance from each other i.e. **static parallel electrode collector.** This design can also be extrapolated in different ways where the magnetic field strength of the magnets could be increased and the distance between the magnets could be varied. Such approaches could lead to highly aligned nanofibers being obtained on this collector set-up.

Also, in the present study the rotating drum and rotating disc collector set-up could not be fabricated. Future work could be done in this area by using cost effective materials for fabrication of these collector set-ups and optimising the parameters involved, changing rotation speed, to obtain highly ordered nanofibers.

Other novel approaches could also be studied and discovered for creation of highly ordered and aligned nanofibers which could have wide applications in various industries such as medical, ceramics, mechanical and become an increasingly interesting area of research.

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