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Design of a High Performance Fiber-producing Machine

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Abstract

The aim of this work is to design a high-productivity, continuously operating fiber producing device utilizing the centrifugal force to yield polymeric nanofibers. The requirements for the design were 1) to provide a capillary-to-collector distance of 50-200 mm that could be adjusted automatically, 2) allow the rotational speed of the spinneret to be changed in the range of 0-25000 1/min and have continuous feeding. The equipment will form the basis of several research topics, such as the creation and study of solid dispersions of drugs, the development of pressure sensors, and the creation of porous filter membranes.

Keywords*: design, centrifugal spinning, nanofiber, control system.*

1. Introduction

Nanotechnology deals with material proprieties and functionality when the dimension of the produced item falls between 0.1 to 100 nm [1, 2]. Nanomaterials exhibit different properties than those of a bulk piece made of the same material. This is due to the nanometer scale dimensions and leads to some interesting properties with regards to the mechanical, thermal, optical, biological, magnetic and electronic behavior [3].

A good example of nanomaterial is fibers, that are used in several industries ranging from batteries, fuel cells, electric components, the air and space industry and drug carriers, to filters for gas and liquid applications. There are several techniques dealing with the production of nanofibers. Double component extrusion, phase separation, pattern synthesis, drawing, electrospinning and centrifugal spinning are a few that could be mentioned [4].

Electrospinning in particular is a well-studied polymeric nanofiber production technique that allows production of fibers below the micrometer range. The setup is simple and easy to use. Several polymers can be used to produce nanofibers with electrospinning. Electrospinning can be of two types: solution spinning or melt spinning. Solution spinning requires the use of a solvent that solubilizes the polymer to yield a polymer solution. This method uses less energy; however the use of solvents could pose an environmental threat. Melt electrospinning utilizes heat to produce a polymer melt for the fiber production. Melt spinning produces fibers with larger diameters, in the couple of 10s of micrometer range and allows little control over the fiber diameter by the process parameters [5]. Electrospinning is a favourable method to produce nanofibers, however it has some disadvantages, such as the employment of a high electric field, the polymer solution or melt has to be electrically conductive and the production rate is very low, 0.01-0.5 g/h.

Centrifugal spinning to produce polymer-based nanofibers first appeared in the literature in the early 2010's. The technique uses centrifugal force to produce nanofiber instead of an electric field as in the case of electrospinning. During centrifugal spinning a head that contains the polymer solution and a few capillaries (**Figure 3**) spins at a high 1/min. Due to the arising centrifugal force a polymer solution jet exits on each capillary and travels from the rotating head to a stationary collector. During the process the solvent evaporates and the solidified polymer fiber deposit on the collector. Centrifugal spinning, even at laboratory scale, has a high production rate, 60 g/h/capillary [6].

2. Centrifugal Spinning Machine

2.1. Design Requirements

The designed centrifugal spinning machine has a similar design and the same working principle to the commercially available models. The objective was to produce a centrifugal spinning machine that could be used for both educational and research purposes at the Sapientia University, Faculty of Technical and Human Sciences – Târgu-Mureș. The design criteria were:

- the polymer solution feeding should be continuous (the majority of the centrifugal spinning machines reported in the literature work in a batch mode),
- the temperature and relative humidity could be measured,
- the speed of the spinning head could be controlled and the maximum speed should be approximately 30000 1/min,
- the capillaries could be changed
- the capillary-collector distance could be altered.

2.2. The Structure of the Centrifugal Spinning Machine

2.2.1. Frame

The frame is made of 30×30 mm Bosch Rexroth aluminum profiles, that are strong enough to withstand the arising mechanical stresses and on the other hand it allows a relatively easy assembly. The profile is anodized, thus it can withstand the potential corrosive nature of the utilized solvents. The frame has a 650×650×650 mm^3 cube shape with a utilizable workspace of 650×650×430 mm^3.

2.2.2. The 3-phase Electric Motor

An APS 6374 brushless DC (BLDC) electric motor was selected to rotate the spinning head (Figure 2). The motor provides a maximum of 3200 W power and a maximum 1/min of 38400. The BLDC motor could be supplied by a maximum of 48 V and the rotation speed control is carried out with an appropriate phase control unit.

2.2.3. The BLDC Motor Controller

The brushless DC electric motors, also known as electric commutation direct current motors (ECDC) are servo motors with a DC feed that has an electrically controlled commutating system. For such electric motors, the current used is directly proportional to the torque, while the voltage is proportional to the speed.

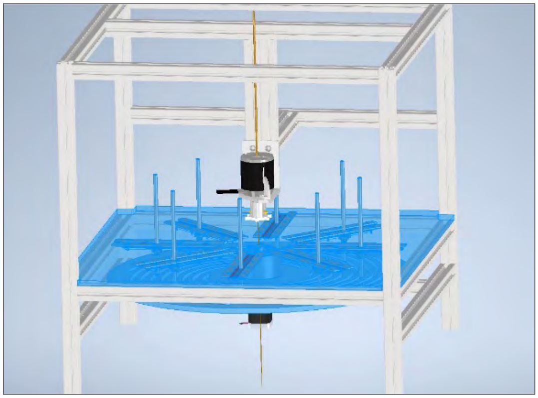

Figure 1. *The 3D image of the designed centrifugal spinning machine.*

Figure 2. *The APS 6374 BLDC electric motor.*

In a BLDC motor the coils (electromagnets) do not move, instead the permanent magnets rotate, and the armature is stationary. The brush-commutator system is replaced with an electric control unit.

2.2.4. The Rotating Head

The rotating head, responsible for the fiber production, is attached to the shaft of the BLDC motor. The continuous feed is accomplished by a syringe pump, that is connected to the rotating head by a copper pipe. A 5 mm diameter hole is drilled in the shaft of the motor along its axis to allow the copper pipe to reach the rotating head, thus allowing the polymer solution to reach the capillaries. The rotating head is designed as an assembly of two pieces to allow for easy cleaning and assembly. The upper piece, 1 in Figure 3, connects to the shaft by a tight tolerance and further secured by two screws. The lower part, 2 in Figure 3, of the rotating head screws on to the first one.

2.2.5. The Collector

The fibers deposit on the collector, thus vertical rods are placed along a circle, the diameter of which can be altered, as illustrated in Figure 5. The working principle of the mechanism that allows the change of the circle's diameter, thus the movement of the collector rods, is similar to that of a lathe chuck. Eight stainless steel rods form the collector placed along a circle with axis parallel to the rotating head. There are two major units to the mechanism: a stationary unit that guides the collector rods, thus the radial movement is possible, and a moving, rotating unit, that contains eight Archimedes spiral shaped channels. The equation of the Archimedes' spiral and the rotating angle of the rotating unit allows the calculation of the exact positions of the collector rods with respect to the rotating head.

2.2.6. The Drivetrain of the Collector

A stepper motor equipped with a speed reducer, 1 in Figure 5, is responsible for the rotating movement of the collector. The speed reducer has a gear ratio of $i = 50$. The motor drives the moving unit of the collector via a toothed belt with a reduction ratio of $i = 14$, 2 in Figure 5, thus providing the required torque.

2.2.7. The Driver of the Stepper Motor

The stepper motor is controlled by a digital DM332T driver. This driver has been chosen due to its dependability and ease of programing. The bipolar stepper motor can be controlled by connecting it to the right connections of the driver. The "PUL" connection is responsible for the number of steps the motor has to take, the "DIR" connection provides the direction of the rotation, and the motor is powered by the "ENA" connection with 5V.

2.2.8. The Central Control Unit

The centrifugal spinning machine will be controlled by a PLC unit, that allows the adjustment of the rotating speed and capillary-collector distance. The PLC unit grants the industrial reliability and flexible programing of the centrifugal spinning machine, that must operate in a continuous fashion. A Siemens Sematic S7-300CPU PLC unit has been chosen for this purpose.

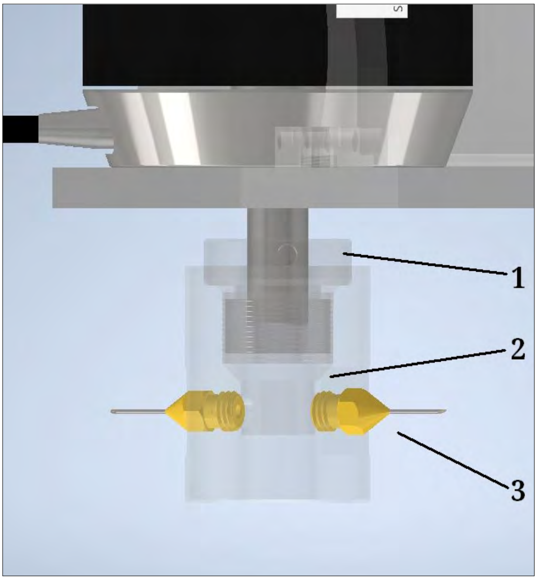

Figure 3. *3D model of the rotating head with the capillaries attached: 1 – upper part, 2 – lower part, 3 – attached capillaries.*

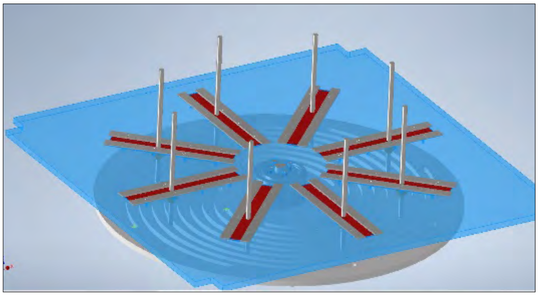

Figure 4. *Circular placement of the collector roads.*

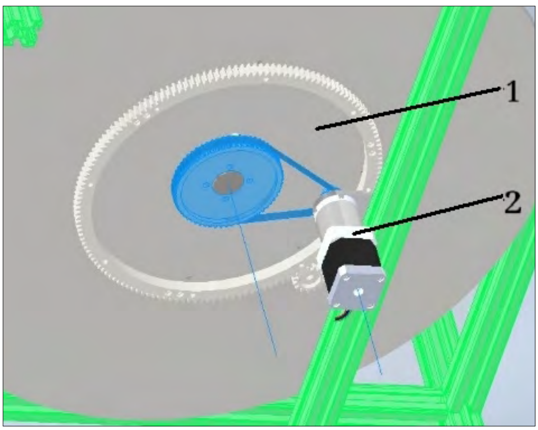

Figure 5. *The drivetrain of the collector: 1 – stepper motor and 2 – toothed belt drive.*

4. Conclusions

In conclusion, the presented design steps result in a continuously operated, automated centrifugal spinning machine that follows the cost-effective design principles.

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