Design and Automation of a vertical electrospinning system for manufacturing nanofibers

Diseño y Automatización de un sistema de electrohilado vertical para fabricación de nanofibras

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Abstract

The objective of this research consists of the design, construction and automation of the electrospinning mechatronic system to obtain nanofibers. As a first stage, the structure of the electrospinning mechatronic system and the distribution, injection and manifold system were designed and built. In the second stage, the open-loop control system was outlined and implemented. It is made up of: control, isolation stage, and the plant. In the first element, the LabView interface and ATmega2560 microcontroller were used to manipulate the variables of the injection speed and distribution of the solution, the speed of the nanofiber collector and the height between the capillary tube and the collector, the magnitude of the temperature and humidity from the environment, also, the graphic interface was developed, the second element consists of isolating the control and power stage in addition to amplifying the command signals and enabling the correction elements, the third element receiving the signals from the power stage to perform the action and produce a change in the controlled variables in the process. With this prototype, it is intended to obtain nanofibers from different polymer solutions for use in the area of catalysis and biomaterials.

Open loop control system, Electrospinning, Control

Resumen

El objetivo de esta investigación consiste en el diseño, construcción y automatización del sistema Mecatrónico de electrohilado para la obtención de nanofibras. Como primera etapa se diseñó y construyó la estructura del sistema mecatrónico de electrohilado y el sistema de distribución, inyección y el colector. En la segunda etapa se esbozó e implementó el sistema de control a lazo abierto está constituido: control, etapa de aislamiento y la planta. En el primer elemento se utilizó la interfaz de LabView y microcontrolador ATmega2560 para manipular las variables de la velocidad de inyección y distribución de la solución, rapidez del colector de las nanofibras y la altura entre tubo capilar y el colector, la magnitud de la temperatura y humedad del medio ambiente, también, se elaboró la interfaz gráfica, el segundo elemento consiste en aislar la etapa de control y potencia además amplificar las señales de mando y habilitar a los elementos de corrección, el tercer elemento reciben las señales de la etapa de potencia para realizar la acción y producir un cambio en las variables controladas en el proceso. Con este prototipo, se pretende obtener nanofibras a partir de diferentes soluciones poliméricas para usarlas en el área de catálisis y biomateriales.

Sistema de control a lazo abierto, Electrohilado, Control

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Introduction

The electrospinning technique, is the simple and low cost method to obtain polymeric fibers or nanofibers from any polymer that can be dissolved or melted (Garcia, 2013, Moghe & Gupta, 2008). In addition, due to the variety of applications; such as in biomedicine and filtration technologies (García, 2013), automotive industry, Aerospace, Nanotechnology, textile (Cano, Tornero, & Naik, 2010), Nano and electromechanical and electromagnetic microsystems, advanced optical components, drug delivery system (Ramakrishna, Fujihara, Teo, Lim, & Ma, 2005, Yu, et al., 2008), Electronic and optoelectronic nanodevices, energy conversion, environmental protection, sensors (Li & Xia, Direct Fabrication of Composite and Ceramic Hollow Nanofibers by Electrospinning, 2004), agriculture and food industry (Morgalev, et al., 2010); Therefore, it has driven the interest of scientists and engineers to produce nanostructures that optimize processes and increase production (Moghe & Gupta, 2008).

The electrospinning process allows obtaining fibers by coaxial stretching of a viscoelastic solution (Teo & Ramakrishna, 2006) or is used for the production of polymeric fibers with a diameter between 3nm and 5µm (Pham, Sharma, & Mikos, 2006).

It consists of an electromechanical system that can manipulate different variables, these are divided into: solution, properties, controlled variables and environmental parameters, i.e., it consists of three main components: a pump for the syringe, a needle attached to the syringe, a grounded collector plate and a high voltage source connected between the capillary and the collector.

The high voltage applied across the needle creates an electric field, when the surface tension of the droplet formed at the end of the needle is overcome by the electric field the droplet is distorted forming a thermodynamic stability on the surface of the solution generating a "Taylor cone" electrospray, which is directed to the collector plate, on the way the solvent evaporates and the polymeric fiber is deposited on the collector, figure 1 (Duque, Rodriguez, & Lopez, 2013, Moghe & Gupta, 2008), by controlling the parameters unique characteristics of the fibers obtained by electrospinning are achieved.

Considering that each polymer and solvent will be different their dissolution parameters, i.e. the concentration of the polymeric solution: the size and morphology of the fibers are related to the polymer concentration. If the concentration is very diluted, the fibers break before reaching the collector plate due to surface tension, otherwise, if it is very concentrated, the fibers will not form due to its high viscosity, causing the solution to pass through the capillary.

Conductivity of the solution: when salts are added to the solution, the conductivity increases and therefore the electrical force for stretching the fiber, this depends on the diameter of the fiber; voltage: this must be higher than the threshold that will generate the Taylor cone that will be expelled towards the collector, a greater stretching will be obtained promoting the reduction of the diameter of the nanofibers; output flow: when the outflow is of larger diameter it will increase the size of the fiber generating defects in this, on the contrary, it decreases the outflow, therefore, it keeps the Taylor cone stable giving time necessary for the evaporation of the solvent before reaching the collector; distance between the needle tip and the plate may or may not have an effect on the thickness and shape of the fiber, causing appearances of lumps or wet fibers. A small distance will prevent the solvent from evaporating and the polymer from coming out in the form of thread, at a greater distance the fiber could break under its weight. (Li & Xia, 2004).

Figure 1 Schematic diagram of the basic equipment in the electrospinning process

Source (Dekker, 1959)

The electrospinning techniques can be horizontal or vertical (Figure 2 and 3). The disadvantage of the vertical position is the possible exit of drops of solution from the capillary to the collector which can fall on the deposited fibers making the surface of the same defective and interrupting the process. To propel the solution through the capillary an infusion pump can be used if working horizontally with cone as capillary, the outflow of the solution can be determined by the force of gravity linked to the viscosity of the solution (Dekker, 1959).

The physical variables that are manipulated in the process are: voltage that applying a voltage between the capillary and the collector in the order of Kilovolts results in larger diameter fibers, (Huang, Zhang, Kotaki, & Ramakrishna, 2003), it was also determined that it reduces the diameter of the nanofibers when a high voltage is applied to it (Sencadas, et al., 2012) and there is the probability of obtaining defective nanofibers (Deitzel, Kleinmeyer, Harris, & Beck Tan, 2001 and Demir, Yilgor, Yilgor, & Erman, 2002), and finally when a high voltage is applied, a higher stretching of the solution is obtained due to the presence of higher coulomb force in the jet and a strong electric field, therefore, the reduction in the diameter of the fibers is obtained (Lee, et al., 2004 and Haghi & Akbari, 2007); The outflow, if the outflow is lower, the deformation of fiber defects will be avoided (Yuan, Zhang, Dong, & Sheng, 2004), and when the outflow is increased the diameter of the fibers increases and possibly the size of the defects (Zong, et al., 2002) and a minimum value of the solution volume at the capillary outlet must be maintained to obtain a stable Taylor cone (Teo & Ramakrishna, 2006); and the distance between the capillary and the collector depending on the properties of the solution the effect on the variation of the distance may or may not have an effect on the shape of the fibers, if the distance is large the fibers will not form under their own weight, especially if they are of small diameter (Li, Wang, & Xia, 2003), a minimum distance is to give the fibers enough time for the solvent to evaporate before reaching the collector, with a distance too large or too small defective fibers are formed (Ki, et al., 2005), and finally the presence of moisture in the fibers obtained small pores were obtained on the surface of the fibers by the increased moisture (Casper, Stephens, Tassi, Chase, & Rabolt, 2004).

Figure 2 Schematic diagram of the horizontal electrospinning system
Source (Dekker, 1959)

Figure 3 Schematic diagram of vertical electrospinning system
Source (Dekker, 1959)

Therefore, in this work the design of the packaging of the mechatronic system, the distribution, height, injection and collector systems, in addition, the open loop control system was implemented to manipulate the parameters (voltage, output flow and distance between the needle tip and the collector) and keep constant the physical variables in the electrospinning process and the human-machine interface (HMI), for obtaining polymeric nanofibers which could be used as biomaterials and in catalysis.

Description of the method

The mechatronic system for the electrospinning process was designed and implemented, consisting of: electromechanical systems such as distribution, height, injection and collector; the bench, where the dimensions of the cabin where the nanofibers will be produced and the drive system were considered.

And finally the control system, to manipulate the speed of distribution and injection of the polymer solution, distance between the capillary and the collector and speed of uptake of the nanofibers, implemented the open loop control system and finally the tests.

Results

The coaxial electrospinning technique is used to obtain continuous nanofibers with diameters in the order of submicrons to nanometers (Doshi & Reneker, 1995), the vertical electrospinning technique was selected (Dekker, 1959); the mechatronic system for obtaining the nanofibers is formed by:

- Electromechanical displacement system, shown in Figure 4, on the chrome bars the height system slides to generate the movement from left to right in conjunction with the electric actuator and the spindle, likewise moving the electromechanical injection system and horizontally distributing the polymeric solution on the surface of the collector.

Figure 4 Isometric view of the horizontal displacement electromechanical system
Source: Own Authorship

- Height system, manipulates the separation between the capillary (needle) and the collector (roller), the height is controlled by the stepper motor that transmits the movement to the spindle generating the vertical displacement; the separation between the capillary and the collector is controlled. Figure 5 shows the front view and Figure 6 the rear view, i.e. the linear bearings that are the guide for the horizontal sliding on the distribution system and the trapezoidal nut that translates to the height system with the movement of the spindle.

Figure 5 Front isometric view of the height system
Source: Own Authorship

Figure 6 Rear isometric view of the height system.
Source: Own Authorship

- Electromechanical injection system, controls the amount of polymeric solution supplied to the collector (see figure 7); the amount of solution depends on the speed of the stepper motor; therefore, it generates the vertical movement to the syringe support, this system is coupled to the height system.
- Electromechanical collector system, it is the one that stores the nanofibers in circular form, they are rolled up in the roller, this is driven by a direct current motor, that is to say, the revolutions per minute are controlled, see figure 8.

- e) Design of the baseplate, to isolate the temperature and humidity of the internal process and the environment, because they alter the formation of the nanofibers and support the weight of the mechatronic system for obtaining the nanofibers, see figure 9.

Figure 7 Electromechanical injection system
Source: Own Authorship

Figure 8 Electromechanical system of the collector
Source: Own Authorship

Figure 9 Mechatronic system baseplate
Source: Own Authorship

Finally, Figure 10 shows the front view of the assembly of the electromechanical systems of the machine to obtain nanofibers.

Figure 10 Front view of the mechatronic system.
Source: Own Authorship

Control system

The open-loop control system was implemented, because the reference variable(s) is not compared with the controlled variable(s), the accuracy of the system depends on the calibration. Figure 11 shows the block diagram for the control of the electromechanical system of the vertical electrospinning process.

Figure 11 Block diagram of the open loop control system of the electrospinning machine.
Source: Own Authorship

The variables controlled in the mechatronic system are: speed of distribution and injection of the polymeric solution, distance between the capillary tube and the collector and the storage speed of the nanofibers in the collector.

For the control of the variables of distribution and injection speed of the polymeric solution, height between the capillary and the collector of each one of the systems, a stepper motor was used for each one and it is controlled by an ATmega 2560 microcontroller.

The stepper motors have a step angle of 1.80 means that it has 200 steps per revolution and the frequency range is from 0 to 625 Hz. Figure 12 shows the control system software, to manipulate the variables of the mechatronic system, in the void loop 1, control the speed of the collector, to adjust the separation between the capillary and the collector, the speed of distribution of the solution to obtain the nanofibers is established; in void loop 2, the initial position of the aluminum plate of the injection system is manipulated, the speed of the polymeric solution supply is set and the mechatronic system is enabled or disabled, and in void loop 3 the magnitudes of the temperature and humidity inside the bench are obtained.

Figure 13 shows the graphical man-machine interface for the control of the physical variables of the electrospinning process; In the distribution stage, it is manually adjusted to the left or right, and its initial state must be in the central part of the horizontal axis and the "start" button performs the automatic distribution; in the height stage, the separation between the capillary and the collector is manually adjusted, In the injection stage, by assigning an event to the "return" button to release the syringe plunger and the "injection" button to activate the automatic option, and finally the temperature reading start button to monitor the temperature and humidity inside the mechatronic system bench.

Figure 12 Software of the control system of the mechatronic system for obtaining nanofibers
Source: Own Authorship

Figure 13 Man-machine interface
Source: Own Authorship

To evaluate the operation of the equipment, a polyacetate solution was used, the operating conditions were: distribution speed at 30 rpm (revolutions per minute), injection speed of 15mm/min, distance of 10 cm between the capillary tube to the collector, with an applied voltage of 20KV, in Figure 14 and 15, the micrographs of the nanofibers of this polymeric solution are presented.

Figure 14 Micrograph of nanofibers with polyacetate
Source: Own Authorship

Figure 15 Micrograph of nanofibers with polyacetate
Source: Own Authorship

Conclusions

The electromechanical systems of distribution, height, injection, collector and control were designed and implemented for the manipulation of the physical variables of distribution and injection speed of the polymeric solution, separation between the capillary and the collector and speed of the collector, and their operation was verified with the obtaining of polyacetate nanofibers. However, each polymeric solution has its own electrospinning operating conditions for obtaining nanofibers. With the implemented equipment, we will begin to search for the feasibility conditions of polymeric solutions to obtain nanofibers.

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