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SIMULATION OF THE STRAIGHT JET MOVEMENT FROM POLYMER INJECTION WITH DRUM COLLECTOR FOR MANUFACTURING OPTICAL FIBERS

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Abstract

This work proposes and evaluates a computer program using open-source platform of easy Java Simulation (EJS), which is specifically designed to simulate the straight jet movement from injected polymer particle onto drum collector for manufacturing of optical fibers. It is believed that it can help ones to prepare polymer injection machines using either electrospinning or extrusion process, as it depends on many factors, such as the initial injections speed, and also the various forces in the machine's environment. The movement was visualized in 3D motion. There are three cases of particle's movements simulated using the program. Three output variables, such as closest distance, elapsed time, and final speed, are also discussed. In addition, this paper provides also the background of machines, the simplified physics equations, the program codes, and its usage.

Keywords: 3D Simulation, EJS, Easy Java simulation, Polymer optical fibers, Straight jet.

1. Introduction

By using an electrospinning machine, there are many fiber-based products, which could be produced. In the optical field, it is possible to utilize it for producing an aluminum-doped zinc oxide nanofibers [1]. Those different final products could be observed from the various sizes of fibers, which could be manufactured using that particular machine. For instance, to produce aluminum-doped zinc oxide fiber, it is better to use electrospinning machine compared to a solar cell. This is due to the need of a co-axial electrospinning machine for solar cell fibers [2]. Apart from the type of products, the length of fiber to be formed also determines how it is collected [3]. Although they use the same kind of material, they may have different shape of fibers. Furthermore, to make it longer, a different process is necessary. A useful example of this can be observed from two different products: fiber sheet and optical fiber. An optical fiber may need a long continuous single fiber. On the other hand, a common fiber sheet from electrospinning is usually short in length and the fibers are crossing to each other. To produce this kind of lengthy fiber, a different process is usually used, including extrusion process [4].

Optical fibers have been widely used in many applications. For example, it is adopted as an optical sensor for glucose detection [5]. It could be used also for very small particle measurement, such as molecules or atoms by incorporating it with piezoelectric microlens [6]. Moreover, as a communication medium, it can be used to increase the bandwidth replacing the conventional electrical wire in the microprocessor [7]. For a particular product of polymer optical fiber (POF), there is a review on its usage for human life safety [8]. Looking at its endless usability, it is undeniable to find out its effective manufacturing process.

There are some studies evaluating the development of optical fiber manufacturing. Prado et al. [9] evaluated the manufacturing of POF using a recycled polymethyl methacrylate (PMMA). In addition, Ebendorff-Heidepriem and Monro [4] microstructured optical fibers using an extrusion process also has been observed. Moreover, a study by Yifang [10] on manufacturing of optical fiber by using an electrospinning machine with a solution consisting of the same polymer of PMMA has been described, where it can be applied for the micro/nano optical fibers. This process includes the conventional electrospinning shot's movement [11]. Furthermore, there have been also programs to simulate the movement for that electrospinning. This can be illustrated briefly by a direct writing technique using Fortran90 [12] and using Matlab [13]. However, there is no study, which is showing the general straight jet movement with a drum collector. This work is trying to bridge both the extrusion process and the electrospinning machine but only for the part of its movement. That is the straight jet movement. However, there might be some limitations to this initial development. First, it was only focused on the straight path from the overall movement of the shot. Secondly, its calculation was only based on a few forces that would be easier to understand. Then the particles from the electrospinning shot were also in bead by bead model as in First In First Out (FIFO) process [12]. A general simulation could be compared also with a FIFO in common case [14] and a monitoring simulation based on a condition [15]. With all those limitations, a 3D visualization and few test cases for the particle's shot from that polymer injection machine with drum collector can be portrayed.

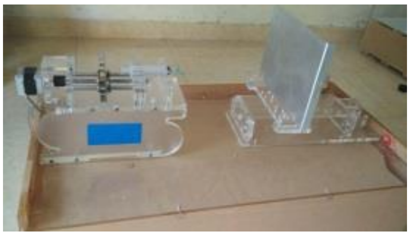
The main objective of this study is to observe the possibilities of producing a lengthy continuous fiber, which is optimally produced using the straight jet condition. It includes the consideration of the pulling force from the drum collector, which is rotating in constant speed. In order to avoid the breakage of the fibers, the optimal conditions from the polymer's injection are tried to be explained by this work. For the development, an open source platform, easy Java simulation (EJS) is used. Hsu et al. [16] mentioned that its usefulness has been exemplified in learning technology. Moreover, this effort is strongly expected to be able to invite more developers who might realize its potentials.

2. Method

There are two things, which should be considered for making a simulation of the shot. First is the machine itself. Then, it is necessary to observe the involved equations for the shot's movement.

2.1. Electrospinning machine

Electrospinning machine may be divided into two types based on its ground collector [3]. That ground collector defines how the products will be formed. In general, the conventional fiber sheets are made by using a ground plate collector, which is known as the direct-writing technique, as shown in Fig. 1(a). This method can be performed directly by injecting the solution from the syringe pump to the plate. The pressure-feeding pump is generally carried out using that syringe pump. Initially, the movement of injection is driven by pressure resulted from the syringe pump. In the case of Fig. 1, it will be from the motor that will rotate and move the small backplate behind the syringe. However, in a further process, the movement is also influenced by high voltage static electric field, which will be shown later in the simulation. In this technique, the size of produced fibers may vary considerably. Those sizes may depend on many factors such as the distance between sprinkler head and collecting plate, flow rate and viscosity of the solution, and many others [11]. Next, a drum collector could be used with the same electrospinning in direct writing technique by replacing the plate, Fig. 1(b). By using this type of machine, it is possible to collect lengthy fiber because it has the drum as a rolling system. In this case, firstly, a polymeric material is inserted into a syringe equipped with a needle. Following needle at the end of the syringe, the pump behind it will push out the solution through the needle and make it behaves like a sprayer. Finally, a high voltage DC source is applied to make an electrostatic force. Thus, the difference is only that the rolling drum is used here instead of a plate. The drum collector is grounded and rotated to accommodate the possibility of lengthy fiber, which will be rolled onto it.



(a) Direct writing method.

(b) Drum collector.

Fig. 1. Electrospinning machine.

Furthermore, the needle, which is being used, is known as Taylor Cone. Its particular size, which is very small, will make it as a nozzle. Then the process of making fibers involves also the electrostatic force of the high electric field as the solution withdraws from the nozzle. The size of the solution coming out of the nozzle can also shrink because of the existing electrostatic influence while undergoing the drying process. Finally, the produced fiber will be accumulated on the collector.

The material movement during the shot at electrospinning machine could be observed in Fig. 2 [11]. The material does not only goes in a straight line. In fact, it is only for a period of time. That shape will be followed soon with a spiral movement as it moves closer to the collector. Its movement starts getting spiral after passing a certain distance and is influenced by many forces. It happens once the speed coming from the initial velocity affected by the pressure at the back of syringe is disappeared. Thus, the movement could be classified into two parts as shown in the figure. The first one is the beginning, which is in the form of a straight jet. Then after a specific distance, the material starts spinning until reaching the collector. During this whole movement, the solution will be dried also. It is commonly used for the solvent evaporation [17].

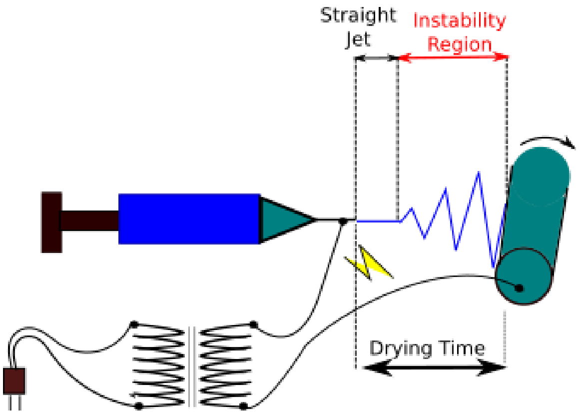


Fig. 2. Material movement from electrospinning.

2.2. Extrusion process

Even though many polymer products are made using electrospinning, there are several kinds of products that will be easier using extrusion process, especially those with a bigger size in diameters. One of its advantages is its possibility to produce long fiber. Meanwhile, different kind of products can be observed from the electrospinning, which is generally in the form of fiber sheets. Thus, normally POF is manufactured using this process.

The extrusion process itself could produce a product, which is in accordance with the forming mold. Thus, to make a single long fiber, ones can use a kind of nozzle for its forming mold. It makes it similar to the electrospinning. The similarity can occur when the material is initially both liquid. However, in most cases, the raw material for extrusion will be in the form of billet [4]. Thus, it is normally using a heater to make it liquid. After that, the process would be the same. It is about squeezing the liquid polymer or polymer solution in the case of electrospinning. It will make the same type of injection also. For both processes, it could go to a similar form of syringe although it may be made of different materials as in Fig. 2.

The other advantage of this process is that it is not necessary to have an electric field so that the machine is much simpler. The way of the injected polymer in reaching the collector can be done manually or mechanically. The main point, in this case, is about how the solution can be drawn for a longer drying process before being collected at the drum collector. The drying process can be carried out along the distance from the needle to the drum collector. It is solving also the most problem of polymer material as it would need a longer path or time in order to be dried or being solidified before being collected.

2.3. Straight jet movement

The overall movement of the material could be identified from a single particle of polymer's material as it comes out as a bead from the syringe [12]. Its movement is formed after various forces around the environment. They are like the viscosity-elastic force, surface tension force, electrostatic force, net coulombs force, gravitational force, pulling force of drum collector, etc. Combination of those forces would make the path's movement of material as shown in Figs. 2 and 3. However, in this program, these forces were simplified into only a few forces because the only concern is the straight path. They will be defined later using classical physics laws [18].

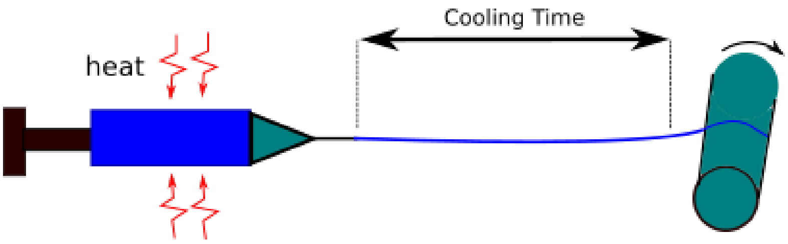


Fig. 3. Pulling to a rotating drum.

The main idea in this study is that outside the syringe, there will be an initial speed which coming from the syringe as the injection is pressed. There would be also a gravitational force, which effects the following mass of material. For the case of electrospinning, its effect would be very small according to its mass but it still has effects because it has a different direction. It can prevent the fiber in reaching the collector as the collector is designed at the side of the injector. Then, there will be also other forces as mention before including the friction between the particle and the surrounding air, which is inside the injection machine. By following the classical Newton laws, this movement could be evaluated as in Eq. (1), which gives either acceleration or deceleration. Since the only concern is the straight path, the value could be assumed into a static value on the average. Although in real cases, the acceleration would be dynamic over time. It is the one, which will make the movement into instability region in the case of electrospinning machine. For extrusion process, there will be a falling extruded material before being pulled by the drum collector. For these different cases, the value is simplified into a single value for this simulation. It could be with either positive for an acceleration, negative for deceleration, or zero in the case of no influences at all, so it can be analysed as a whole. Therefore, it can be used for machine preparation.

$$\sum F = F_{ss} + \vec{F}_g + F_{others} = m\vec{a} \tag{1}$$

Firstly, Eq. (2) shows the force from stress and strain of the material which could represent the material viscosity or its elasticity. For the electrospinning machine, it will be more into the viscosity as its material will be more liquid than the one, which is used in the extrusion process. The extrusion will be closer to the elasticity. However, both of them should be responded as stress and strain, which can be defined as the extended length of material, which is $\Delta L/L$. The stress and strain are equated by Young's modulus of the material, which is written by using variable E.

$$\frac{F_{ss}}{A} = E\frac{\Delta L}{L} \tag{2}$$

By following the Bernoulli's equation, Eq. (3), the material's initial speed can be assumed. The pressure which causes the stress is represented by F/A, in which A is a syringe's cross-sectional area. The force F will give pressure over the syringe. For POF, the pressure would be around 1-7 MPa [4]. It is much bigger compared with common electrospinning machine. The mentioned pressure for POF before would be then equal with 0.03-0.10 mm/min [4]. Meanwhile, for electrospinning machine, a PMMA solution with 25% of concentration was injected with a flow rate of around 200 l/h [10]. It was with a nozzle diameter of 0.21 mm. Note that these numbers are only given to provide an overview of the real experiment's conditions.

$$p + \tfrac{1}{2}\rho v^2 + \rho g h = const. \tag{3}$$

Then, a gravity force in Eq. (4) is also influencing the movement, which is pretty familiar in classical physics law. Even though it is considered easier to be implemented, its value usually is much smaller than the other forces due to its particle's mass in the case of electrospinning. This designed program tries to follow the real machine, which has been described before in Fig. 1(b), where the collector is at the side of the syringe in a horizontal line. It will make its shot becoming perpendicular to this force. The difference in direction will make the injection's shot falling as in a common extrusion process.

$$\vec{F}_g = m\vec{g} \tag{4}$$

The speed can be commonly written as in Eq. (5). It will become the base of the animation from this simulation, which is known as evolution. The variable will be defined once. Then, its value will change according to the program, which will be defined later.

$$v = \lim_{\Delta t \to 0}\frac{\Delta x}{\Delta t} = \frac{dx}{dt} \tag{5}$$

The initial speed is a result of all forces inside the syringe, which has been discussed before by using Bernoulli's equation, Eq. (3). As the material's bead is released from the syringe's needle, the speed will be affected by various forces, which have been described earlier as an acceleration value, Eq. (1). The first variable, *v*, will change according to the influence of the second variable, *a*, as the position variable, *s*, is changing according to the speed, *v*. All of them are following the Newton Law. Correlates the acceleration with the particle's speed and position, three equations can be defined in Eqs. (6) to (8):

$$a = \frac{dv}{dt} \tag{6}$$

$$s_{n+1} = s_n + vt \tag{7}$$

$$v_{n+1} = v_n + at \tag{8}$$

The equations will be used later on for the simulation using java programming. The variables will be also defined one by one in the EJS platform.

3. Result and Discussion

There are two issues, which can be discussed as the results of the study. Firstly, it relates to the program itself, which includes the interface, visualization, and equations. Secondly, it is about the shot's possibilities, which can help on finding the best injection's parameters. Therefore, it can be applied to the real machine.

3.1. Easy java simulation

The simulation can use EJS [19] as replacement of a commercial platform like Matlab. By using the software, it was easy to arrange a simulation using physics laws [20]. The design was started by defining the axis for the movement. Then, the syringe and other components from the polymer injection machine can be modeled. By designing each individual component, the visualization of overall movement has the potential to be applied to the real machine [21].

All components for this simulation can be observed in a View Page in Fig. 4. The visualization was conducted using a 3D environment, which is labeled as Display3DPanel. It was in the form of a 3D box, which enclosed all the other models. Inside it, there were four 3D models. Firstly, the trajectory was used to track the path of the particle's movement. It would mark every point, which was passed by the particle. That was the reason why particles from the injected material were assumed in the FIFO model so the following particles could be represented using this 3D model. Secondly, *groundCollector* could be modeled by the drum collector. It was also possible to animate the object by rotating it so it is able to visualize a real rotating drum.

Thirdly, velocityArrow was very useful in showing the vector's direction of the particle. Its position would be following the particle. The length of the arrow could also be adjusted to represent its vector magnitude in real time. Finally, the particle could be used as a particle's model. It was simply designed as a little ball, which will be moving from left side of the 3D box to the rotating drum's model. All of these models would represent the real polymer injection machine with a drum collector.

The equations were possible to be implemented in EJS. In fact, it could be the most useful feature of the software. There are two parts in these equations. The first is the ordinary differential equations. Secondly, there were related to physics laws for the position, velocity, and acceleration. The ordinary differential equations could be inserted in the evolution page, which could be observed in Fig. 4. It was used for defining the evolution of axis and variables. In this 3D environment, all three axes of x, y, and z were defined. Then, it is followed by the speed variables for its relationship with corresponding accelerations, which are on the right column. The variable could be modified later on as it will be useful in simulating the particle's movement in different rate's value. They were all input with standard mathematical equations, which was using a differential form of $d(x)/dt$ (5-6) as shown in Fig. 5(a). It helped the software in making the animation over time or known as evolution.

After that, equations for classical physics laws could be written in the evolution page, which is shown in Fig. 5(b). In this page, most of the physics equations for each axis will be defined as explained before as Eqs. (2), (3), and (4). First, two equations were on each axis for the distance and the velocity. Finally, one equation was for the time. Following these, the gravitational force was also defined. It could be observed at the x-axis. There was an equation, which affects the value of v_x.

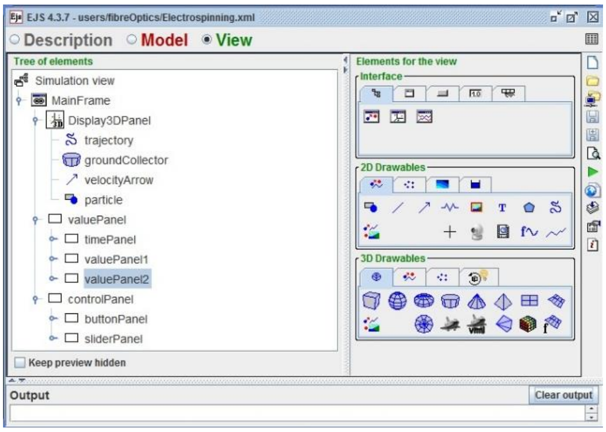
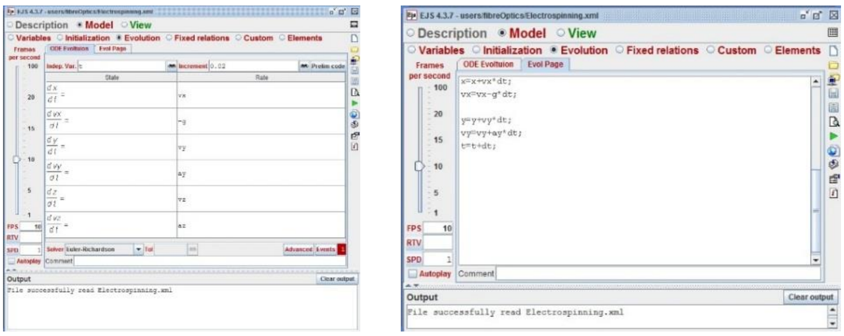


Fig. 4. Components of view.



(a) Evolution page. **(b) Position, velocity and acceleration.**

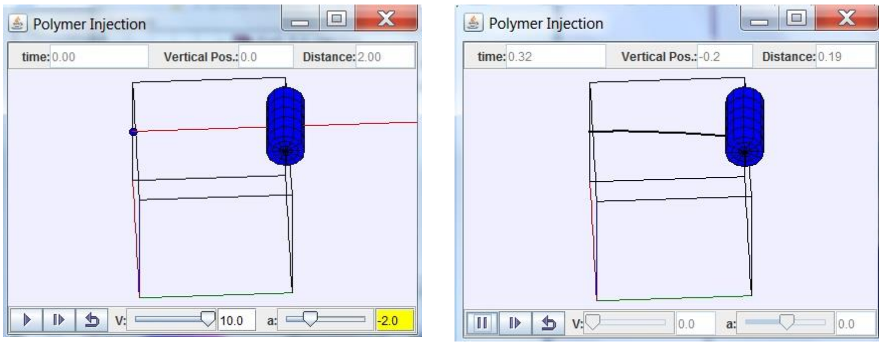
Fig. 5. Code snippets of simulation.

3.2. Shot's possibilities

The instability region of electrospinning, which is shown in Fig. 3, the initial speed injected by the pump force, has been run out. The straight jet condition should happen when there was still enough speed that brings the particle in straight condition. This initial development would set out the basic simulation to measure the possibilities of the injection's shots by limiting only in this condition. It would make the possibility of finding the right injection's feeding speed on a real machine for particular machines with a drum collector.

Details of the initial computer's program were available in *Appendix A*. By using this initial version of the program, there were three conditions, which could be simulated in order to observe the possibilities of a straight jet path for a fixed distance between the syringe's needle and the rotating drum collector. There were two input parameters, which would be used here. The first one was the initial speed resulted from the pressure. The second parameter was the acceleration as a result of various resultant vectors of many forces in assumption. Using the two parameters with a constant distance, a simulation on how the straight jet would behave was able to be demonstrated.

The first case was an ideal path of the electrospinning, which was shown in Fig. 6. There was enough initial speed even though there was a deceleration as shown at the bottom panel in Fig. 6(a). The simulation was using 10 as initial speed and -2 as the acceleration. That negative value of acceleration could represent the deceleration coming from the air frictions, or other forces with an as discussed before at part II-C. Running Motion, which was shown in Fig. 6(b), can be obtained by clicking the first button at bottom left corner. It showed directly possibility of the resulted fiber's position in seconds. In this case, the particle reached the drum collector. In real condition, this position could also be shifted but this visualization had given a hint already for the best initial speed.

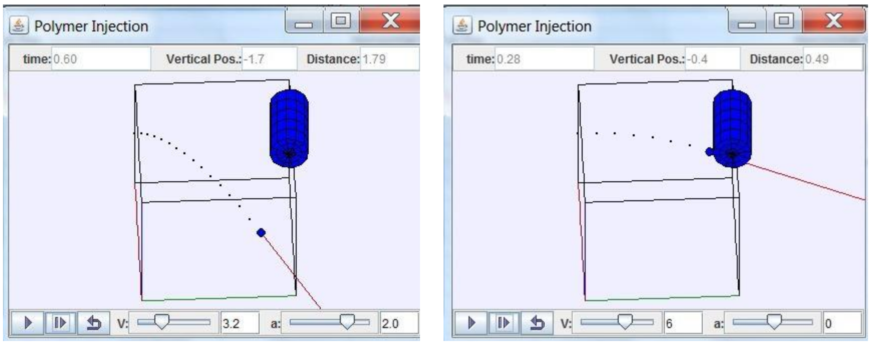


(a) Initial values. **(b) Running motion.**

Fig. 6. Ideal path.

For an unreached path, its simulation could be observed in a Step Motion in Fig. 7(a). This happened when there was only a small initial speed. The simulation was using 2 as initial speed and 2 as the acceleration. It was not enough for particles to reach the collector although there was an acceleration that supports its movement to the collector. However, this simulation had much affected with the gravitational force as it has not enough speed and not enough acceleration to reach the drum collector.

The third condition was the possibility of the particle when it was only reached the edge of the drum. It could be observed also in a Step Motion in Fig. 7(b). It was using 6 as initial speed and 0 as the acceleration. In this mode, the motion of the particles could be examined. It was in an incremental step over a period of *dt*, which was around 0.04 second. Using this mode, all the physics values, such as elapsed time, vertical position, and the distance to the collector were possible to be analysed. They are all can be obtained at the top panel of the program, while all of the input conditions could be inserted at the bottom panel. These values were used also for further examination at the following tables. Note that there were no units for its values as it could be just estimation over the real numbers and could be used with a scaling factor, which would be explained later. It would be useful for only giving an indication of the possible shot's trajectories with a given condition of initial speed and acceleration for the machine preparation.



(a) Unreached path. **(b) Reaching the edge.**

Fig. 7. Other possible paths in step motion.

To simulate the variation of the acceleration, a number of acceleration's values were defined within the range of -2 and 2 in Table 1. Then to find the best injection speed for the machine preparation, a range of initial speeds was also listed within 2 and 10. These distance's values were obtained from the simulation. It was displayed at the top right corner at the program as shown in Fig. 6 with a value of 2.00. From these simulation results, it could be observed that injections speeds, 2 and 4 were having unreached paths. They were colored in Red at Table 1. An example that was given in Fig. 7(a) was thickened in Table 1.

Simulations with distance closest values around 0.5 were showing its position quite closed to the collector. They were colored in Blue at Table 1. An example, which was given in Fig. 7(b), was thickened also in Table 1. The other conditions, which had a value less than 0.45, were actually reaching the collector. They were colored in Black in Table 1. An example, which was given in Fig. 6(b), was thickened also in Table 1 but this one had a different value. The value at picture should be the final distance when it was hit the collector, while the value at the table was the closest distance before it stopped either by hitting the collector or falling to the ground. Overall, the data already showed three possible conditions of the injected particle into the drum collector.

Table 1. Closest distance for different initial speed and acceleration.

Distance		Acceleration				
		-2	-1	0	1	2
Initial Speed	2	2.08	1.99	1.91	1.84	1.79
	4	1.31	1.12	0.96	0.94	0.80
	6	0.52	0.5	0.49	0.47	0.44
	8	0.30	0.29	0.44	0.42	0.41
	10	0.44	0.43	0.42	0.41	0.39

Following the distance, the elapsed time for the particle's movement was also shown at the top panel but at the left side. Its value was corresponding with the minimum distance to the collector, which was shown before at Table 1.

It also meant that it was the time for the particle to reach the closest distance. They were all summarized in Table 2. Three same cases as before, which were shown in Figs. 7(a), 7(b), and 6(b), were also thickened in the red, blue, and black color group, respectively. The time data showed a similar trend as the distance. They were also getting smaller for cases where its path was getting close to collector although there was not much difference with the little variation in acceleration. Some even have the same value for the same speed. This implied the slow initial speed as an indicator of unreached fiber and having longer elapsed time.

Although that could be solved by increasing the pump pressure, some electrospinning material might need that long drying time as it is necessary to evaporate 98 % of the solvent [17]. Thus, it might depend on the electrostatic force of a high DC voltage in the range of several kV to several tens of kV [3], to attract those unreached fibers. For injections with the extrusion process, it could just go with the highest of possible injection speed, and the cooling time could be done mechanically to the room temperature at approximately 23 ºC [9].

Table 2. Time elapsed to reach corresponding distance vs. different initial speed and acceleration.

Time		Acceleration				
		-2	-1	0	1	2
Initial Speed	2	0.60	0.60	0.60	0.60	0.60
	4	0.52	0.48	0.44	0.44	0.40
	6	0.32	0.32	0.28	0.28	0.28
	8	0.24	0.24	0.2	0.2	0.2
	10	0.16	0.16	0.16	0.16	0.16

At the last, the final speed at the corresponding time for the specific case of initial speed and acceleration was calculated and listed in Table 3. It showed the corresponding speed at the time listed previously in Table 2 with the condition of closest distance to the collector at Table 1. The values were obtained from the speed input parameter at the bottom panel as it will change following the movement. The final speed could also indicate the final straight jet condition before reaching the drum collector as described before for the closest distance in Table 1. Its direction might be different as it depends on the resultant vector of forces in that 3D simulation's environment. Those directions of final speed could be observed easily from the program as shown in Figs. 7(a), 7(b), and 6(b) for the unreached path, arrived at edge, and ideal path respectively. Overall, it showed a different trend compared to both Tables 1 and 2. It had a higher final speed for those particles with the closest distance, and having shorter elapsed time. Compared with the time data, for electrospinning, which had been suggested to have longer elapsed time, its final speed will be much slower. In fact, that is exactly where the resulted fiber speed might not be corresponding with drum collector's speed which usually in thousands of rpm rotating speed [3]. The best speeds were called as the alignment speed. Those might need intuitive conjectures. For extrusion, it could just use the highest injection speed and the drum's rotating speed could be made similar to one of the simulated final speeds.

Table 3. The final speed at a corresponding time vs. different initial speed and acceleration.

Final speed		**Acceleration**				
		-2	**-1**	**0**	**1**	**2**
Initial speed	**2**	0.8	1.4	2.0	2.6	3.2
	4	3.0	3.5	4	4.4	4.8
	6	5.4	5.7	6	6.3	6.6
	8	7.5	7.8	8	8.2	8.4
	10	9.7	9.8	10	10.2	10.3

Overall, the program was possible to run and giving three kinds of result. They were the minimum distance, elapsed time, and final speed. These values could speed up the process of finding optimum condition from real experiments. For electrospinning machine, the acceleration could be adjusted with the high voltage and its spinning movement. The higher values would need a higher voltage. Then, for the extrusion process, the acceleration would be about the pulling mechanism. It would depend on the pulling force and the elasticity of polymer solution. The positive value could come from the pulling force of the drum collector. Meanwhile, the negative value might come from the deceleration of the elasticity of the polymer.

However, to use the program for the real machine experiments, a scaling factor must be taken into account because there was no input for the raw material parameters. To use simulated final speeds, a scaling factor could be used. For example, an initial speed of 0.10 mm/min as a reference speed for POF discussed before in (3) could use a factor of 100 to make it as 10 in the simulated speed unit. The final speed could be calculated using the same factor. Thus, ones could try the drum speed, which could pass the fibers at 0.097-106 mm/min as the simulated final speed. By having these simulation values, some suggestions on how to avoid fiber's breakage could be conducted easily by a simple mapping besides the intuitive conjectures. The next development of the program should include also the materials physics parameter, such as Modulus Young value, so a better suggestion for the preparation of polymer injection machines could be given.

4. Conclusions

In this study, a simulation model was developed for preparing the polymers injection machine with a drum collector for producing POF. A program based on EJS has been initially developed. Using this program, three possible cases of polymer injection paths have been tested and summarized in three tables corresponding to each individual output variable. The first was the cases for unreached paths where particles would not arrive at the collector. In the second case, there was a condition where the particles would be arriving quite close to the edge of the collector. Finally, as an ideal path, there was the particle, which would hit the collector. Moreover, based on the simulations, it was possible to observe three output variables which could describe the condition of the particle, such as minimum distance, elapsed time, and final speed as shown in Tables 1 to 3, respectively. All of those output variables can give hints on preparing two kinds of polymer injection machines, which were using electrospinning and extrusion process. The input parameters of the program were the injection speed and approximation of the machine environment's acceleration. It is considered that it becomes possible to connect this to the real machines experiment with a proper scaling factor and simple mapping.

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Nomenclatures

A	Acceleration
F	Newton force
F_{cl}	Coulomb force
F_{es}	Electrostatic force
F_g	Gravitational force
F_{ss}	Stress and strain force which is related to the material
T	Time
V	Speed

Abbreviations

EJS	Easy Java Simulation
FIFO	First In First Out
IDE	Integrated Development Environment
POF	Polymer Optical Fibers
PMMA	Polymethyl methacrylate

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Appendix A

Computer Programme

A computer's program code could be downloaded from Sourceforge Respiratory. To run the computer program, it is required to have Java JRE (Java Runtime Environment) which should be available at Oracle website. The computer program is in a form of the executable file of the jar. It has been tested using Java JRE 1.7. For discussion and feedbacks, Sourceforge Web Forum could be used.

Program summary:

Program title : Polymer Injection

Program summary URL :

https://sourceforge.net/projects/polymerinjection/

Licensing provisions : Open Source License

Distribution format : .jar

Programming language : Java.

Requirement : Java JRE 1.7, available at

https://www.oracle.com/

Operating system : PC OS: Linux, Windows.

Development IDE : Easy Java Simulation (EJS) 4.3.7.

Forum for Discussion:

https://sourceforge.net/p/polymerinjection/discussion/