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ANALYZING THE EFFECT OF NOZZLE DIAMETER IN FUSED DEPOSITION MODELING FOR EXTRUDING POLYLACTIC ACID USING OPEN SOURCE 3D PRINTING

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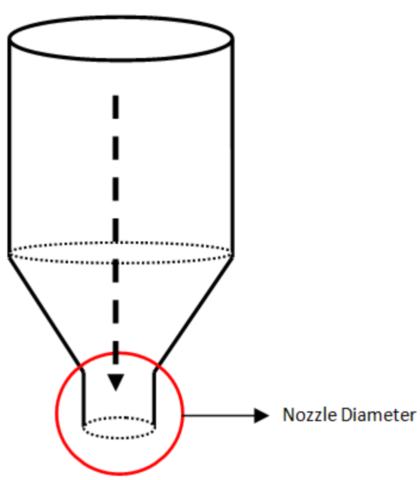
Graphical abstract



Abstract

Fused deposition modeling (FDM) is one of the Rapid Prototyping (RP) technologies. The 3D Printer has been widely used in the fabrication of 3D products. One of the main issues has been to obtain a high quality for the finished parts. The present study focuses on the effect of nozzle diameter in terms of pressure drop, geometrical error as well as extrusion time. While using polylactic acid (PLA) as a material, the research was conducted using Finite Element Analysis (FEA) by manipulating the nozzle diameter, and the pressure drop along the liquefier was observed. The geometrical error and printing time were also calculated by using different nozzle diameters. Analysis shows that the diameter of the nozzle significantly affects the pressure drop along the liquefier which influences the consistency of the road width thus affecting the quality of the product's finish. The vital aspect is minimizing the pressure drop to be as low as possible, which will lead to a good quality final product. The results from the analysis demonstrate that a 0.2 mm nozzle diameter contributes the highest pressure drop, which is not within the optimum range. In this study, by considering several factors including pressure drop, geometrical error and printing time, a 0.3 mm nozzle diameter has been suggested as being in the optimum range for extruding PLA material using open-source 3D printing. The implication of this result is valuable for a better understanding of the melt flow behavior of the PLA material and for choosing the optimum nozzle diameter for 3D printing.

Keywords: Nozzle diameter; pressure drop; fused deposition modeling; open source 3D printing

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1.0 INTRODUCTION

Fabrication technology has vastly improved over the years with much innovation to meet the demand. Rapid prototyping (RP) technology is one of the fast growing technologies since the 1960s [1]. As is well known, there are several types of RP technology, including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS) and Stereolithography (SLA) [2,3,4]. In general, the RP process begins by importing the models from CAD data, converting them into STL format and then sending the information into the RP machine, which will create the material layer-by-layer until the last layer is completed [5]. Between these processes, FDM has an advantage over the others as the use of material in filament form offers flexibility and reduces the resident time in the melting chamber [6]. In general, the FDM process is quite simple since the filament will push by the roller to the melting chamber and be extruded through the nozzle layer-by-layer with complex geometries [2] as shown in Figure 1.

Despite being one of the most advantageous technologies for fabricating 3D models, there is an issue regarding the cost of FDM. Research has been performed to minimize the cost in terms of processes and other components [7]. Due to this, an open-source 3D Printer, which is usually referred to as the RepRep (replicating rapid prototype), has been introduced with low cost [8]. As the software and design are freely available online, it is suitable for home fabrication and research purposes [9]. One of the designs of RepRep 3D printing is termed delta and has a three-stepper motor to move the shaft [10]. A recent study demonstrates that RepRep 3D printing has been modified to be a versatile application of materials and processes and costs less than $1000 (US dollars), which is a sign that 3D printing has become much cheaper due to the availability and accessibility of the technology [11].

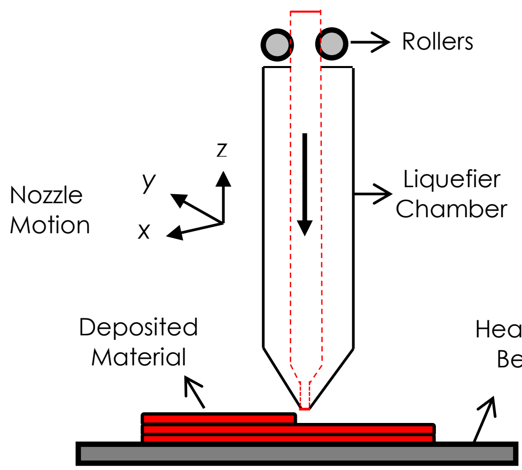


Figure 1 Basic mechanism of the FDM process

The development of 3D printing has had a great impact on the medical field since the need for a variety of materials which can fulfill any particular application has increased [2]. A synthetic biomaterial such as polylactic acid (PLA) has the biodegradability that is needed particularly in orthopedics, since it has the ability to act as a platform for generating tissues [12,13]. A study investigated the suitability of extruding PLA to observe the properties of the final product (such as mechanical strength) and its potential in scaffold design [14].

So far, many research studies have been conducted by manipulating the process parameters to find the best quality for the finished parts in terms of both their accuracy and mechanical properties [15]-[20]. The impact of the process parameters such as air gap, layer thickness, printing speed, and printing temperature on the finished parts will be analyzed and the most influential process parameters will be emphasized.

Even though a low-cost 3D printer brings changes to the community in making 3D products, there are some drawbacks with this technology. The products' quality is still questionable, leaving some areas for improvement when producing quality finished parts. Simulations have been performed using finite element analysis (FEA) to predict the flow behavior of the material along the liquefier [15-17]. A study was performed by Ramanath [21] using FEA that observed the flow behaviour of polycaprolactone (PCL) by changing the nozzle diameter from 0.2 mm to 0.4 mm. The results showed that smaller the diameter higher is the pressure drop. An accurate part finish depends on the consistency of the road width. To have a consistent road width, the pressure drop along the liquefier needs to be kept to a minimum. However, the study does not mention an optimum nozzle diameter for the printing process. Uptill now, there has been no investigation on which nozzle diameter provides a better quality of finished parts.

The force from the stepper motor required to push the filaments through the liquefier is constant. The pressure from the motor needs to be monitored and the nozzle's geometry, which affects the pressure, needs to be found. The present research has focused on analyzing the effect on the pressure drop using FEA analysis by varying the nozzle diameter and also the nozzle diameter's effect on the printing time. The product's accuracy and consistency depends on the pressure drop; thus, observing the pressure drop is vital. In addition, to have an efficient extrusion process, it is crucial to focus not only on the accuracy but also on the extrusion time. This study suggests the optimum nozzle diameter for open-source 3D printing, which was developed for this research, using PLA as a material.

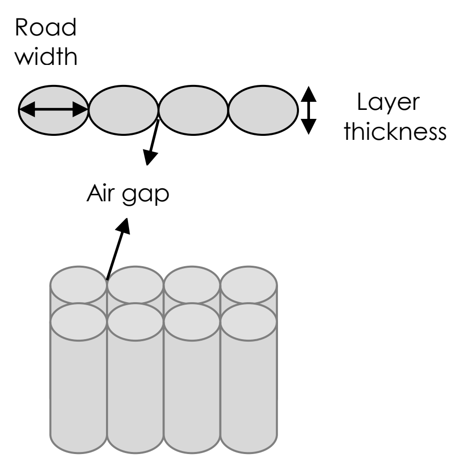


Figure 2 Printing process parameters

2.0 METHODOLOGY

The flow behavior for PLA material was investigated using FEA by considering all the boundary conditions. By varying the nozzle diameter, the flow of the material inside the liquefier was observed to see the effect on the pressure drop. The difference in nozzle diameter also affects the printing time. To analyze these issues and suggest the optimum nozzle diameter in terms of accuracy and printing time, calculations and an experiment were conducted. Figure 3 is a flow chart of the overall research methodology.

This study provides an understanding of the nozzle diameter's effect on the finished parts by considering some limitations. This research's main limitation is that the simulation undertaken may be slightly different than the actual condition. It is assumed that the flow is in steady state, whereas in the real situation the material's flow is changing due to fluctuating heat from the liquefier. However, this simulation provides a prediction of the material's flow behavior along the liquefier and verifies the difference in the products' quality when parts were printed using different nozzle diameters. The parts were examined in terms of accuracy and consistency of the road width.

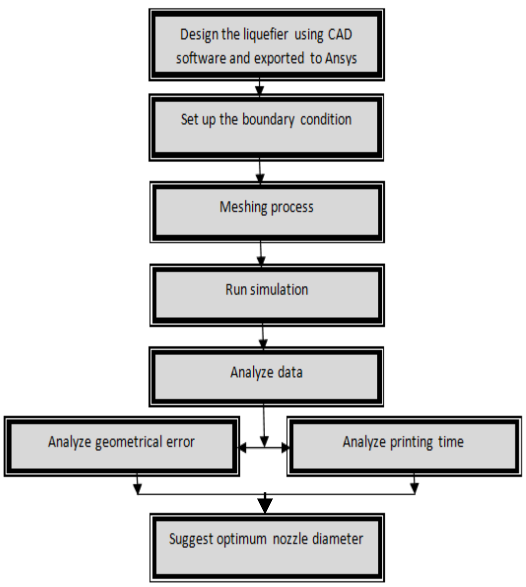


Figure 3 The general procedure for the research

2.1 Material

The present study has chosen PLA as the material for the simulation. The material's properties need to be identified as they need to be used in the FEA to observe the flow behavior of the PLA material. The PLA material's properties as provided by the supplier (Emlabz Technology Sdn Bhd, Kuala Lumpur, Malaysia) are shown in Table 1.

2.2 Finite Element Analysis

Geometric modeling needs to be developed to simulate the PLA flow through the nozzle. A new open-source 3D Printer has been developed as shown in Figure 3 and Figure 4. The machine was designed using the Autodesk Inventor Software (Autodesk, USA) and all the products were assembled in the Politeknik Kuching Sarawak Laboratory. 3D printing is easily controlled using the Repetier-Host Software, and it is low cost and suitable for research purposes. The simulation was conducted using FEA, which is ANSYS Workbench 14. 2D models were developed using ANSYS Workbench and 3D models were developed using Autodesk Inventor Software (Autodesk, USA) and exported into ANSYS Workbench 14. The simulation of the flow along the liquefier length is as shown in Figure 5(a) and Figure 5(b).

The boundary condition is very important for conducting an FEA simulation. The 3D Printing process is practically in an unsteady state, but to simplify the process, it is assumed to be in a steady state with no change in the flow over time [15,16]. Some other assumptions were considered in this simulation [15,16]:

i. As there is no change in the flow, this indicates laminar flow;
ii. The PLA flow velocity at the wall through the liquefier is considered as zero because the melt is assumed to be adhering to the wall;
iii. The liquefier temperature is considered as constant since it is perfectly insulated.

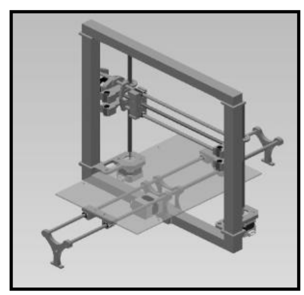


Figure 3 Design for new 3D printing using CAD software

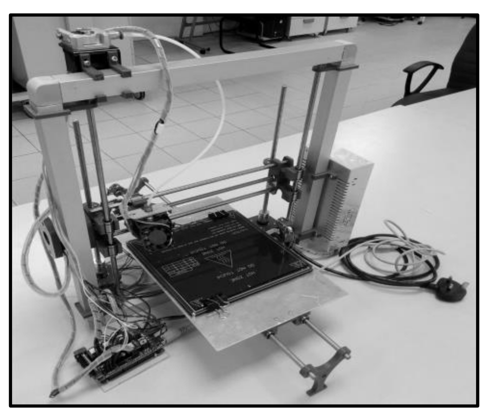
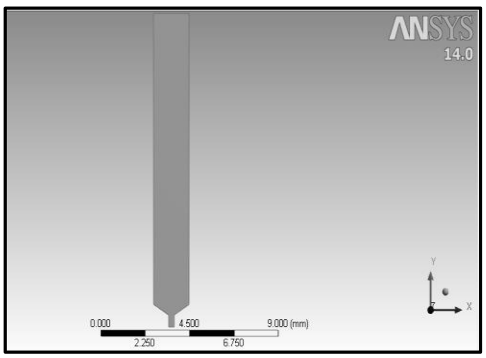


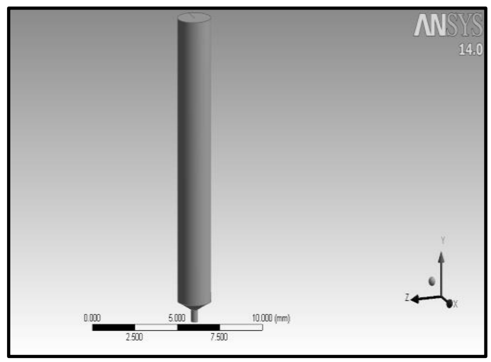
Figure 4 The new 3D printing

Table1 Properties of PLA material

Specification		**Testing Condition (Mode)**	**Measurement** for Testing	**Measurement Unit**
Physical Capability	Density	-	1.25	g/cm^3
	Specific Heat		1800	J/kg-K
	Thermal Conductivity		0.13	W/m-K
Machine Capability	Film Thickness	Tested	25	µm
	Tensile Strength	MD:25 µm	103	µm
		TD: 25 µm	145	µm
	Elongation	MD:25 µm	180	%
		TD: 25 µm	100	%
Thermal Capability	Glass transition Point (temperature)	DSC	57.8	°C
	Melting Point (temperature)	-	160	°C
Optical Capability	Gloss	20°C, 25.4 µm	90	-
	Transparency	25.4 µm	2.1	%



(a) Geometrical modeling in 3D



(b) Geometrical modeling in 2D

Figure 5 Design modeling for the simulation

The geometrical parameters were set up as shown in Figure 6. The four parameters that were set for conducting the FEA simulation using the default configuration were the length of the liquefier (L is 12 mm), the filament diameter (D is 1.8 mm), the die angle (θ is 120°) and the nozzle diameter (d has been set to be 0.4 mm). All these parameters were fixed except the nozzle diameter, which were changed from 0.2 mm to 0.25 mm, 0.3 mm, 0.35 mm, and 0.4 mm. The filament feed rate was set up for 0.3 mm/s that determines the inlet velocity as 0.0031 m/s. The temperature at the liquefier chamber wall was set to be 159.85°C (433K) and the inlet temperature was 26.85°C (300K), which refers to the PLA material's melting temperature as shown in Figure 6 [24].

For the meshing process, fine meshing with the combination of a tetrahedron was used to achieve accurate results [23]. The double precision mode was selected for the FEA setting as well as for thousands of iterations to obtain a stable and better result.

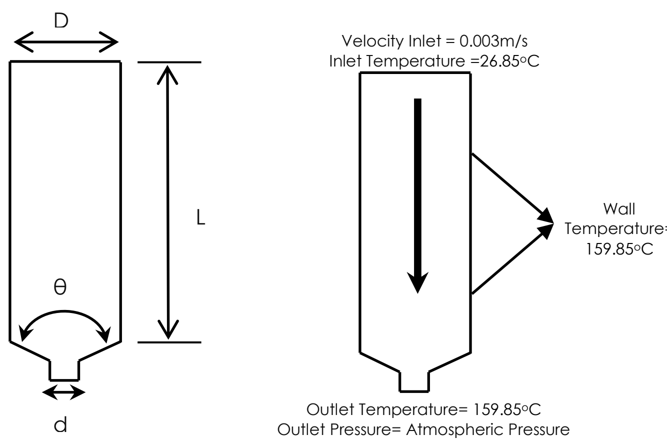


Figure 6 Boundary condition for the FEA simulation

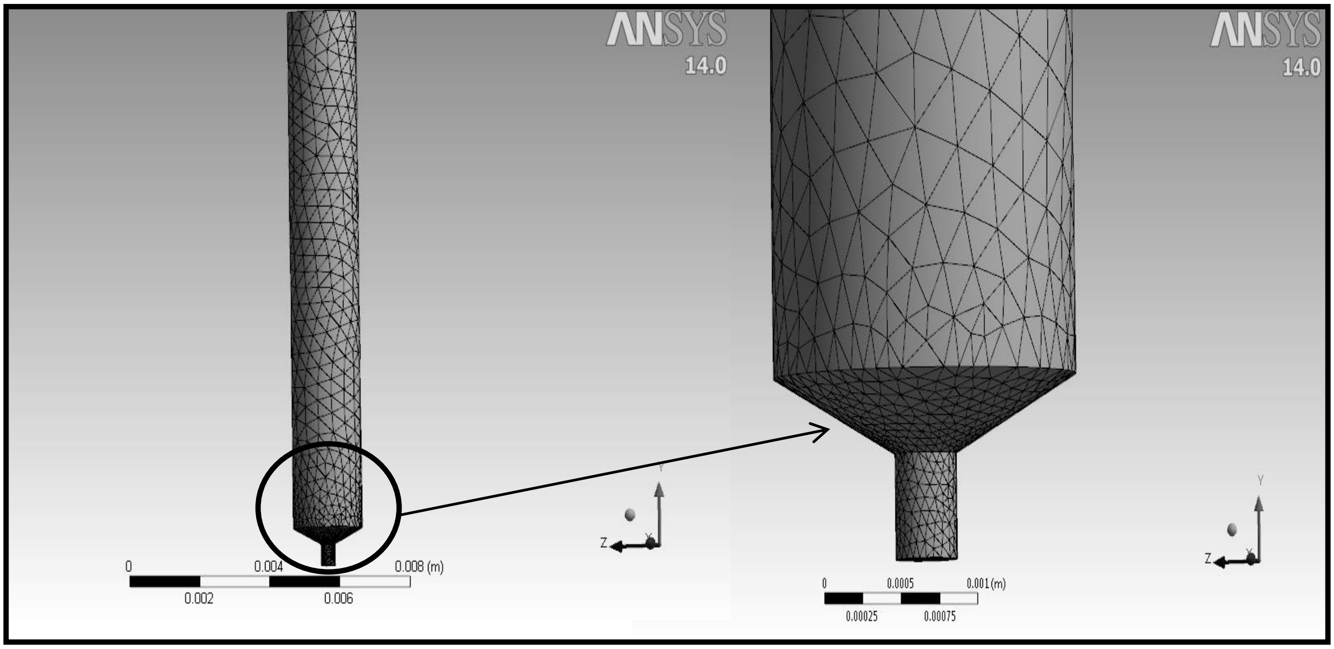


Figure 7 Meshing process for FEA simulation

3.0 RESULTS AND DISCUSSION

The main concern here is in observing the pressure drop effect when the diameter of the nozzle is changed from 0.2 mm to 0.25 mm, 0.3 mm, 0.35 mm, and 0.4 mm. The pressure drop can be estimated by mathematical modeling from equation 1 until equation 4. The idea behind this is that as the pressure drop along the liquefier varies, it significantly affects the road width of the finished parts which in turn affects the product quality [21], [23]. Minimizing the pressure drop to be as low as possible is the key to obtaining a consistent product. The pressure drop can be calculated along the liquefier length corresponding to area (A)L_a,(B), and (C)L_b, and mathematical modeling was used in previous studies for each area as described below (Refer to Figure 5): [16, 17].

$$\Delta P = \Delta P_A + \Delta P_B + \Delta P_C \quad (1)$$

$$\Delta P_A = 2L_a \left(\frac{v}{\phi}\right)^{1/m} \left(\frac{m+3}{(D/2)^{m+1}}\right)^{1/m} exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (2)$$

$$\Delta P_B = \left(\frac{2m}{3\tan(\theta/2)}\right)\left(\frac{1}{d^{3/m}} - \frac{1}{D^{3/m}}\right) \times \left(\frac{D^2}{2}(m+3)2^{m+3}\right)^{1/m} \times exp\left[\alpha\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (3)$$

$$\Delta P_C = 2L_b \left(\frac{v}{\emptyset}\right)^{1/m} \left(\frac{(m+3)(D_1/2)^2}{(D_2/2)^{m+3}}\right)^{1/m} exp\left[\left(\frac{1}{T} - \frac{1}{T_\alpha}\right)\right] \quad (4)$$

The total pressure drop, ΔP, is the sum of all the pressure drops from all regions starting from regions **A**, **B**, and **C.** $\emptyset$ and m are the power-law fit parameters and θ is the nozzle angle [16, 17].

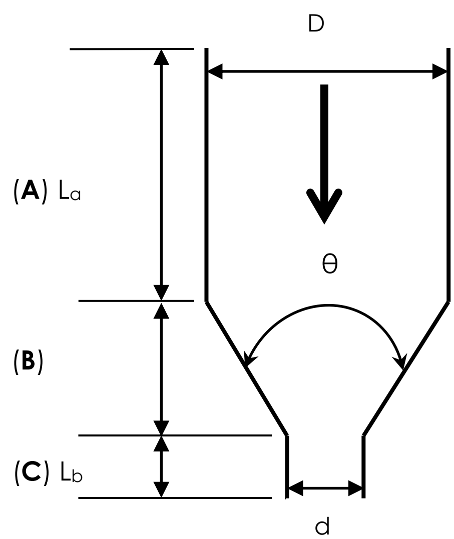


Figure 8 Pressure drop area from (A), (B), and (C)

The pressure drop can be seen in Figure 9 as the nozzle diameter is varied between 0.2 mm to 0.25 mm, 0.3 mm, 0.35 mm, and 0.4 mm. As the outlet nozzle diameter becomes narrower, the pressure drop becomes higher. The same trend has been observed in Ramanath's research [21] who observed the melt flow behaviour of polycaprolactone in fused desposition modeling. Comparing the 0.2 mm and 0.4 mm nozzle diameters, 0.2 mm of nozzle diameter produces a pressure drop that is almost three times higher. This shows that nozzle diameter plays a major role in affecting the pressure drop. Other research by Liang and Ness [25] demonstrates that increasing the ratio L/D (where L is the length of a conical shape and D is the outlet diameter) means that when D becomes smaller, it contributes to a higher pressure drop. Selecting the optimum nozzle diameter is vital for maintaining consistency in extruding the material.

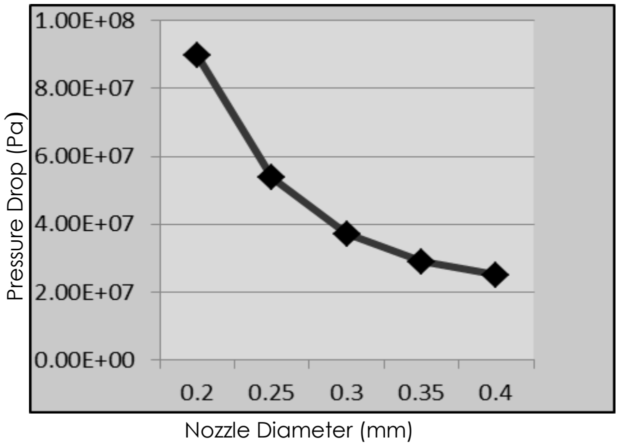


Figure 9 Decreasing pressure drop as the nozzle angle becomes larger

To verify that the nozzle diameter does affect the road width of the finished part, the samples were printed using 0.2 mm and 0.3 mm nozzle diameters. The difference in the road width can be observed by referring to Figure 10 and Figure 11 below; it is observed that the 0.3 mm nozzle diameter is more consistent in providing the same road width for every layer. Meanwhile, the 0.2 mm nozzle diameter provides thin layers but is inconsistent, which can also be seen from the side of the parts. This shows that the pressure drop caused by the different nozzle diameters does affect the road width which in turn affects the accuracy of the finished parts.

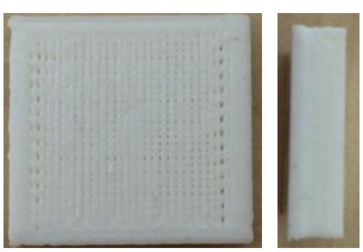


Figure 10 Consistent road width printed by the 0.3 mm nozzle diameter

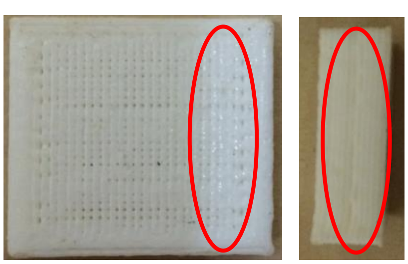


Figure 11 Inconsistent road width printed by the 0.2 mm nozzle diameter

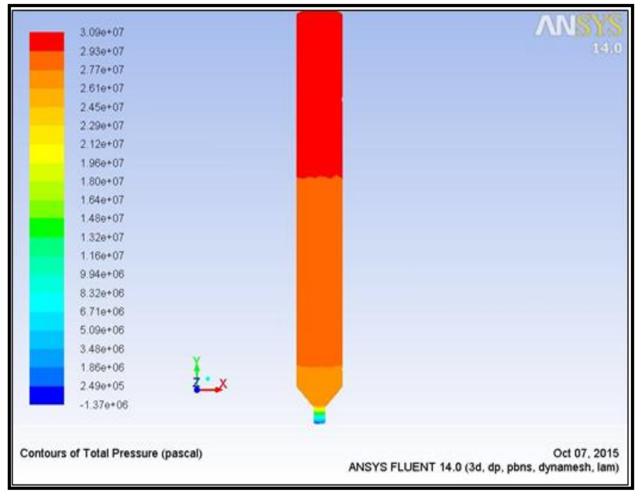


Figure 12 Pressure drop along the liquefier chamber and at the nozzle tip

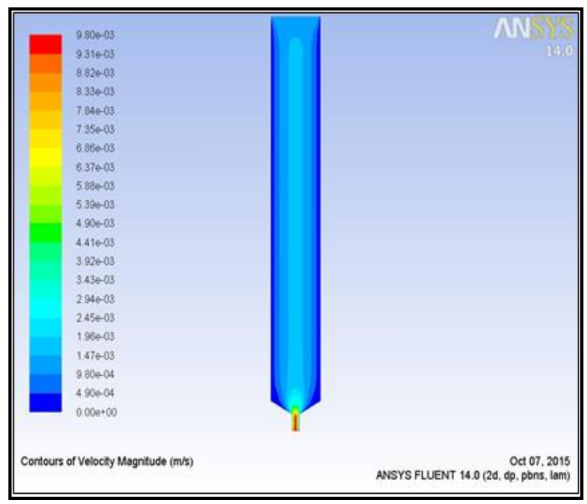


Figure 13 Profile of the velocity along the liquefier chamber

According to Brooks [27], the geometrical error of an angle printed with a circular nozzle can be calculated using equation 5 below:

$$Error = \frac{R}{\sin\left(\frac{\beta}{2}\right)} - R \quad (5)$$

where R is the radius of the extrusion orifice and β is the angle of the modeled geometry [27].

By referring to equation 5, it can be observed that the error is increased when the nozzle diameter becomes larger. When it comes to accuracy, the smaller nozzle produces better accuracy for the extruded product. However, while referring to the simulation, the smaller the nozzle diameter, the higher will be the pressure drop. A higher pressure drop will affect the consistency and quality of the road width. Choosing the correct and best diameter for the nozzle can increase the quality and consistency of the final product.

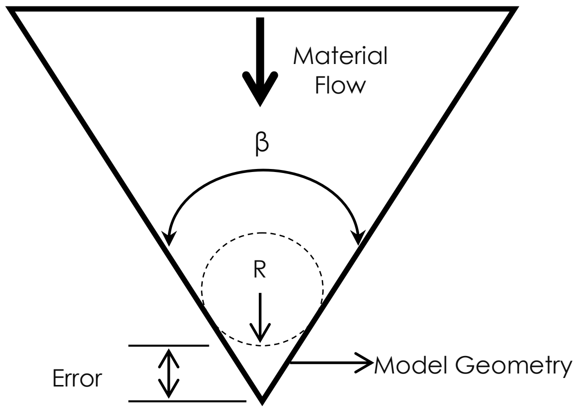


Figure 14 Error of circular nozzle (Adapted from Books [26])

The nozzle diameter also has a significant impact on the extrusion time. Assume a high percentage of infill, which is to be assumed as 100% solid (can be set in the percentage of infill option), the extrusion time can then be calculated as follows: [26]

$$Extrusion\ time = \frac{V}{\mathrm{d} \times f \times l} \tag{6}$$

v is the volume of the printed part (mm^3), d is the outlet nozzle diameter (mm), *f* refers to the filament feed rate and *l* is the total layer thickness [26].
To verify this theoretical calculation, a square part has been printed to measure the extrusion time which is in second (s) and all the data has been recorded in Table 2. Consider the filament feed rate f = 3.01 mm/s, the nozzle diameter = 0.4 mm and *l* = 2 mm for a default configuration.

Table 2 Comparison between the theoretical calculation and the experiment for extrusion time

Volume	288 mm³	450 mm³	648 mm³
Theoretical	119.6	186.9	269.1
Experimental	123.6	183.0	263.0
Percentage error (%) *(E-T) / T*	3.3	2.1	2.3

From Table 2, the percentage error exhibits a small value which verifies this theoretical formula. The graph of extrusion time versus volume was plotted for different nozzle diameters as in Figure 15.

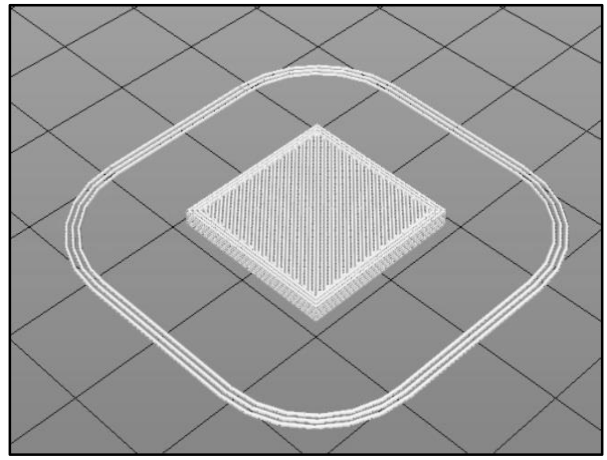


Figure 15 Slicing square part using Repetier-Host Software

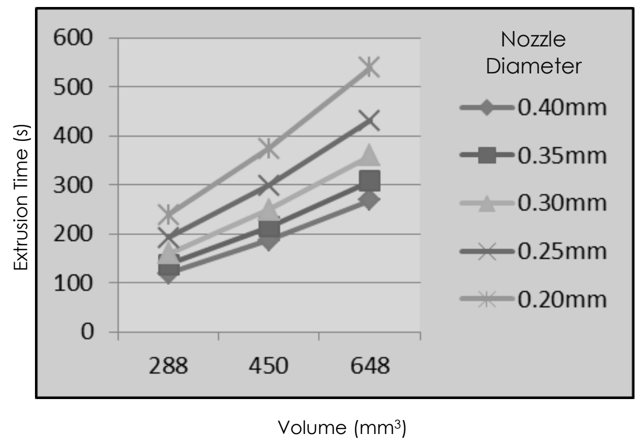


Figure 16 Comparison of time taken between different nozzle diameters to extrude square parts

It is certain from the graph that the bigger the nozzle diameter, the smaller is the time taken to finish the part. By analyzing all these factors, choosing the right nozzle diameter will provide an optimum extrusion process, not only in terms of accuracy but also in terms of extrusion time. Considering the simulation when the nozzle diameter is 0.2 mm, the pressure drop is the highest, which significantly affects the road widths even though the calculated error is smaller. Consistency during the extrusion process is vital to obtain a good scaffold design since the force required to push the filament is constant [21]. To obtain an effective extrusion process, the factors of accuracy and extrusion time must be in the optimum range. Figure 17 demonstrates that 0.2 mm and 0.25 mm nozzle diameters contribute the highest pressure drop and with these results, they are not considered to be in the optimum range. Between the 0.3 mm and 0.4 mm nozzle diameters shown in Figure 17, the difference in the pressure drop is not too high, but when it comes to geometrical error, 0.3 mm is the smallest. By considering the lower error, the pressure drop and the extrusion time, the 0.3 mm nozzle diameter can be suggested as being in the optimum range for extruding polylactic acid.

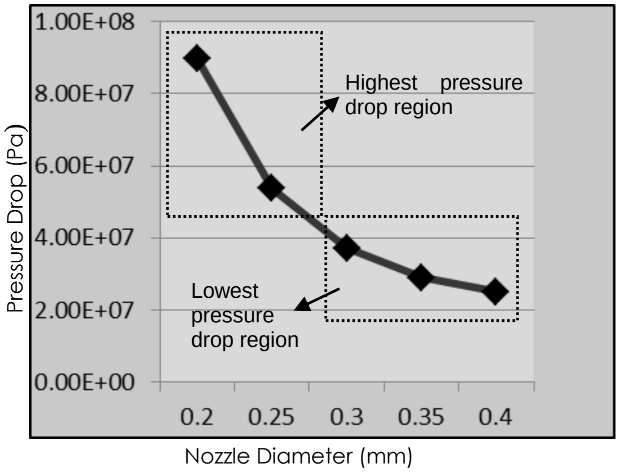


Figure 17 Decreasing pressure drop as the nozzle angle becomes larger

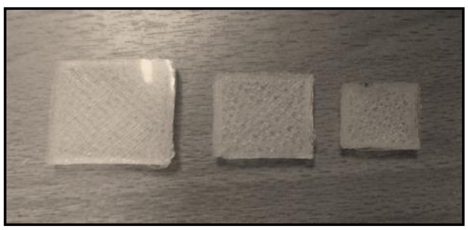


Figure 18 Printed samples with different volume for measuring extrusion time

4.0 CONCLUSION

Nozzle diameter is one of the factors that affects the pressure drop along the liquefier. The key to obtaining the stability and consistency of the scaffold design is to have the minimum pressure drop, since from the simulation results, it is apparent that varying the nozzle diameter does affect the pressure drop. The highest pressure drop is contributed by the 0.2 mm and 0.25 mm nozzle diameters, which is the reason why they are not chosen to be in the optimum range. Choosing the optimum nozzle diameter is very important, not only in terms of accuracy but also in terms of the extrusion time. In this study, by using open source 3D printing which has been developed for the research purpose, the 0.3 mm diameter nozzle has been suggested as the optimum range for extruding PLA material using an open-source 3D printer.

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