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NOZZLE DESIGN FOR FUSED DEPOSITION MODELLING 3D PRINTING OF CARBON FIBRE REINFORCED POLYMER COMPOSITE COMPONENT USING SIMULATION METHOD

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ABSTRACT

This This paper focuses on the extrusion process of carbon fibre reinforced polymer (CFRP) in Fused Deposition Method (FDM) of 3D printing. Particularly, the polymer used is polylactic acid (PLA). There is a need to investigate towards getting an optimum nozzle design with respect to its material type and geometry so that CRFP can be extruded efficiently layer-by-layer using a simulation method. Modelling of different nozzle geometries, extrusion flows and the ensuing analyses were conducted using a simulation software. In particular, various parameters such as nozzle die angle, outlet diameter and material were varied in this study. As a result, different filament fluid behaviours (relative velocity, pressure and temperature) and the heat flux distributions in the extrusion flow and within the nozzle, were obtained and analysed. As a conclusion, the best design obtained through this study is a nozzle with a brass material, 120o die angle and 0.4 mm outlet diameter.

1. Introduction

Manufacturing nowadays are looking towards to more versatile processes which able to cope with the current complex design features and structure to be produced. Thus, the three-dimensional (3D) printing which is one of the branches of manufacturing is selected for its adaptability in industries. 3D printing can provide an agile design solution and faster interactions with parts created for most of the user especially in production as it can be use on numerous materials selections [1]. Among 3D printing advantages are to reduce production costs especially for low to middle production volume, reduces the time taken for a product produced rather than the traditional methods, and the production on demand

In 3D printing manufacturing, several types are introduced as encouragement to industries for further development and advantages of each type. Commonly used in industries are the FDM, Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) [2]. Each type depends on the material use while giving exclusive benefits. Most of manufactures goes on reinforcing composite materials use to further strengthen the design structures for instance the usage of carbon fibre with Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS) [3].

Carbon fibre composites are one of the recognised materials in manufacturing and production industries for its lateral and tensile strength [4]. The matrix structure of carbon fibre which are with strong graphite atoms bonded together forming crystal approximately aligned parallel to the long axis producing several quality values including having low weight, high stiffness, high tensile strength, high chemical resistance, temperature tolerance and low thermal expansion. Most of the marketed or produced carbon fibre are composites that combined with other materials such as thermoplastic resin to form carbon fibre reinforced polymer which creating properties of higher strength-to-volume ratio. [5]

For the low-cost 3D printer to have wide variety of applications in fabricating 3D model, the technology requires further analysis and development to fulfil the requirement in terms of consistency and stability of the extruded parts. Recent research only focuses on the process parameters to improve the finish parts. However, the hardware system is also an important element that contributes to the better extrusion process, hence providing good products. Thus, this brings in an opportunity to further add on to this technology. One of the most important parts is the 3D printer head, which comprises of nozzle, liquefier and heating element, as shown in Fig.1.

Fig. 1A *3D printer nozzle [7]*

It is the heart of the machine as the quality and compatibility of the material being extruded depends on the 3D printer head. In addition, the properties of materials need to be investigated to allow smooth extrusion, consistent, accurate and not to clog the printer head during extrusion process [6].

As the main component of the printer, it is crucial to have a nozzle that meets different requirements in FDM, depending on filament feed, time consumption, materials and final quality finish. The FDM nozzle structure generally separated into structure control device, feeding mechanism, throat cooling unit, cooling device, pipe assembly and nozzle hot end parts.

Constant improvement of technology in FDM 3D printing is affecting increaseduse of composite properties of the carbon fibre in manufacturing industries.Thus, proportional to carbon fibre reinforced plastics (CFRP) material advancement, the nozzle correspondingly must advance as well to cope adequately to the composite material advancement using FDM 3D printing. In order to produce optimum recommendation of nozzle geometry and material for CFRP printing, some parameters were analysed via simulation and thus improving the nozzle capability.

2. Nozzle Specifications And Pre-Processing Parameters

The nozzle design influences the flow and the thermal behaviour of the filamentgoing through it. The focus of this section is to study the effect of the geometries of exit nozzle design on the liquid CF-PLA behaviour. Ageneral nozzle design was selected for manufacture after considering simulation results by Sukindar et al. [6]. The cases of nozzle for case 1 and case 2 is shown in Table Iwere divided into four individual designs.

TABLE I. *Nozzle Specifications*

Material / Parameter	Range	Case 1, Design A (110° angle & 0.4 mm diameter)	Case 1, Design B (120° angle & 0.4 mm diameter)	Case 2, Design C (120° angle & 0.4 mm diameter)	Case 2, Design D (120° angle & 0.6 mm diameter)
Total Nodes		24004	24615	24615	2412
Total elements		15853	16287	16287	1594
Maximum aspect ratio	10 - 30	8.794	9.9974	9.9977	5.985
Percentage of elements with aspect ratio < 3	90 – 99	99.4	99.6	99.6	99.6
Percentage of elements with aspect ratio > 10	Ideally = 0	0	0	0	0
Element size	0.5 mm	0.5	0.5	0.5	0.5
Tolerance	0.025 mm	0.025	0.025	0.025	0.025

The design for case 1 is constant with 0.4 mm diameter outlet with varying the die angle of 110o and 120o while the case 2 are kept constant of die angle of 120o with 0.4 mm and 0.6 mm diameter. Each design was fixed with the length, L of 12 mm and inlet diameter of 1.8 mm. The nozzle model was generated using SolidWorks as shown in Fig. 2 and Fig. 3 for inner view.

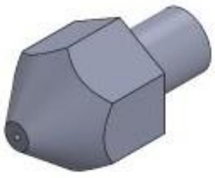


***Fig. 2** The working design of 3D printer nozzle [7]*

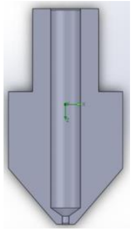


Fig. 3 *Section view of the inner nozzle model*

For each of the geometry models developed, it is important to consider on the aspect ratio of the model; the maximum aspect ratio range of 10-30, percentage of elements with aspect ratio < 3 between 90 to 99.99 % which depend on the complexity of the model geometry and percentage of elements with aspect ratio > 10 to be ideally 0. Table I also shows the aspect ratio (AR) for model developed, where aspect ratio is defined as the shortest length of the element to the longest length of the element.

For the simulation to run, it is important to apply the boundary condition to obtain the desirable workflow of the process. Parameterswere set between 195oC-250oC for temperature and 0.07 m/s of feed speed as recommended by several authors [2], [8]. The pressure of 101.325 kPa was applied at the nozzle outlet to solve for thermo-fluid analysis. Then, the velocity was assigned at the nozzle inlet. It was assumed that there was no friction produced between solid-liquid boundary. In thermal analysis, the geometry models were applied with thermal loads of temperature and convection; temperature of 523.15 Kelvin (250oC) then the convection coefficient was assigned according to their respective material values; brass is about 20 W/m2.K, stainless steel is 17 W/m2.K and 15 W/m2.K for hardened steel.

Each of the nozzle inlet and outlet in the models need to be capped to create a water-tight model. The SolidWorks software provides a tool to achieve this water-tight model called LID creator, before applying the LID each geometry needs to check geometry for the correct and accurate symmetry of the geometry.

Based on the aspect ratio, selection for ideal model design are designs B and C which are of similar design but different cases. The designs yield percentage of elements with aspect ratio < 3 of 99.6 and maximum aspect ratio which is more acceptable value of 9.997.

Fig. 4 shows the fixed boundary condition at the inlet with 0.07 m/s velocity and temperature of 250 oC which at the outlet, the temperature 250oC and the pressure of an atmospheric pressure at 101.325 kPa.

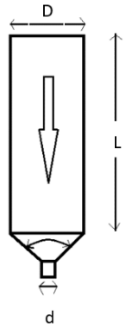


Fig. 4 *Boundary condition [6]*

To study the thermal fluxes occurring on the nozzle metal materials, three materials selected were brass, hardened steel and stainless steel. Except for stainless steel which already included in SolidWorks material library, the hardened steel and brass were created as new material profile customization from the library.

Liquid CF-PLA behaviour during the motion was investigated by using three different parameters which are pressure, temperature and velocity. The behaviour of the liquid depends on the geometry which produce substantial surface area or volume that affect the pressure per region which the parameters condition was concluded [9]. Table II shows the representative of the parameter conditions for the internal volume of the CF-PLA liquid flow.

TABLE II. *Parameter Conditions*

Parameter Condition	Maximum value	Minimum value	Average value
Pressure, Pa	101325	100000	100662.5
Temperature, Kelvin (°C)	498.15 (220)	468.15 (195)	483.15 (207.5)
Velocity, m/s	0.07	0.00	0.035

The maximum pressure was set at 101.325 kPa whilst the minimum pressure was 100 kPa. From these minimum and maximum values, the average pressure was 100.663 kPa. The variation of these pressure shall not affect the stability of extrusion process.

Table III shows the volume zone inside the models.

TABLE III. *Volume Zone Inside The Models*

	Case 1		Case 2	
	A	B	C	D
Geometry Volume (mm3) Zone	110° angle with 0.4 mm diameter	120° angle with 0.4 mm diameter	120°angle with 0.4 mm diameter	120° angle with 0.6 mm diameter
1	30.536	30.536	30.536	30.536
2	0.539	0.541	0.539	0.613
3	0.063	0.063	0.063	0.141

Fig. 5 shows the zones for the internal volume of the CF-PLA liquid flow.

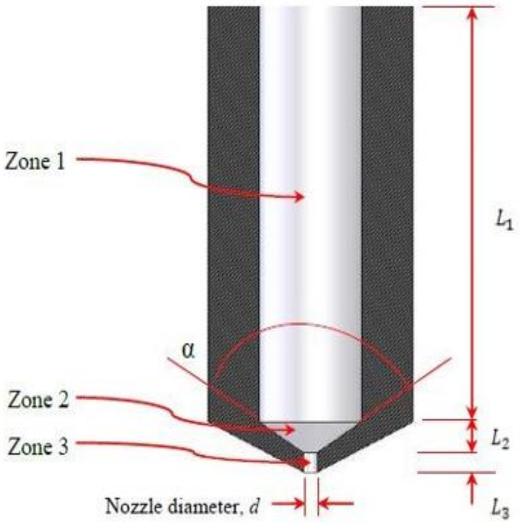


Fig. 5 *Nozzle specific zone [10]*

From the threaded/cylindrical region which the nozzle receives thermal energy up to 523.15 Kelvin (250 oC) to heat up and liquefied the CF-PLA filament. The exposed outer region of the nozzle has experienced bulk ambient temperature of 493.15 Kelvin (220 oC) and by the material convection coefficient, the heat convection occurred.

Every model designed has an individual temperature distribution profile and rate of heat transfer which could be observed by the colour change from red to blue colour. With the objective to observe the heat flux profile on the surface model, the 0.4 mm diameter circular nozzle with brass as solid material was taken as the basis of the design in order to compare between the other materials thermal profile. Throughout the extrusion process, steady state and isothermal conditions were assumed whereby, the temperature at the end of nozzle is equal to the extrusiontemperature.

The effects of the different design of nozzle on the performances of filament flow, with variations of die angle degree and diameter, relative velocity, pressure, and fluid temperature distribution in the fluid domain of the nozzle were analysed. While, heat fluxes on solid models were observed and explained accordingly to require consistent molten filament flow.

3. Simulation Results

A. Thermal simulation Results

In Fig. 6, The temperature fluxes of brass, hardened steel and stainless steel are shown.

Red colour represents the maximum temperature whilst the blue colour region shows the minimum temperature of the fluxes.

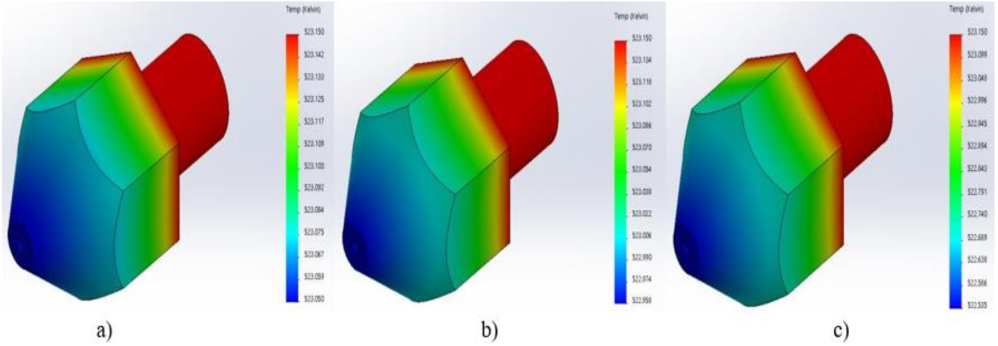


Fig. 6. *Temperature fluxes of brass (a), hardened steel (b) and stainless steel (c)*

Convection mode of heat transfer took place at the exposed nozzle tip contributed to the heat loss. By comparing the three designs, the brass nozzle showed the preferable heat transfer rate which is revealed by the minimum temperature in the blue zone at approximately 523.050 Kelvin (249.9 oC), as compared to the hardened steel which recorded lower temperature of 522.958 Kelvin (249.808 oC) and stainless steel of 522.535 Kelvin (246.385 oC). By choosing brass as solid material, the heat flux between element on the model can be minimized without causing abrupt changes in the flow rate through the nozzle.

B. Fluid flow performance

Fig. 7 is referred. The model is displayed as if cut by planes and faces that user specify, to show the internal construction of the model. Each produced result can be animated to show real-time motion of the simulation and shows the fluid behaviour. Cut plot view flow data results on plane view allows investigation of the inner volume or fluid motion. The cut plots contour parameter is changeable to other values that satisfy the case study which is the pressure, velocity and temperature.

Fig. 7(a) shows that the fluid pressure is constantly experience internally at maximum of 101325 Pa. Fig. 7b) shows the fluid temperature near the outlet wall experience the highest at 523.15 Kelvin (250 oC) while at zone 1 undergo mixed temperature of 492.59 to 517.04 Kelvin (219.44-243.89 oC). Fig. 7c) shows an ideal flow velocity formed on 0.07 m/s on printer. From the simulation, it was observed that the nozzle has a 0.07 m/s flow at centre inner fluid volume and a mix of velocity of 0.039 to 0.062 m/s near the wall due to the laminar flow.

Table IV shows the values at different zones for Case 1, Design A. Similarly, the figures and tables for Case 1, Design B (Fig. 8 and Table V Case 2), Design C (Fig. 9 and Table VI Case 2) and Case 2, Design d (Fig. 10 and Table VII Case 2) are shown accordingly.

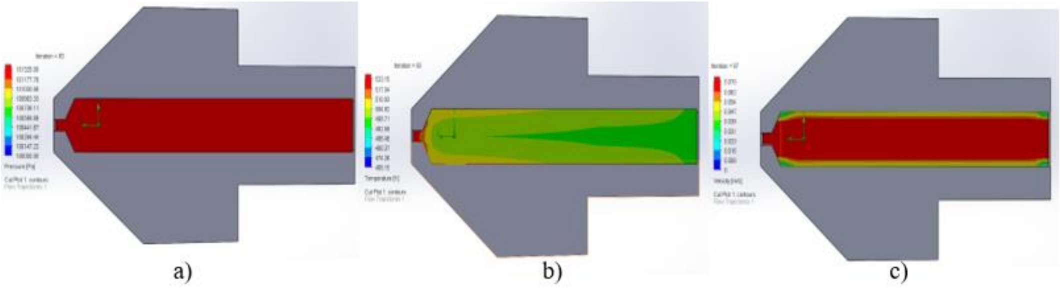

a) b) c)

Fig. 7*Cut plot of design A (1100 angle and 0.4 mm diameter) showing fluid pressure, temperature and velocity, respectively*

TABLE IV*. Parameter Valuesat Different Zones For Case 1 (Design A)*

Case 1	Zone	Pressure, Pa	Velocity, m/s	Temperature, °C
A	1	101325	0.04-0.07	225.56-231.82
	2	101325	0.07	231.82-243.89
	3	101325	0.07	250.00

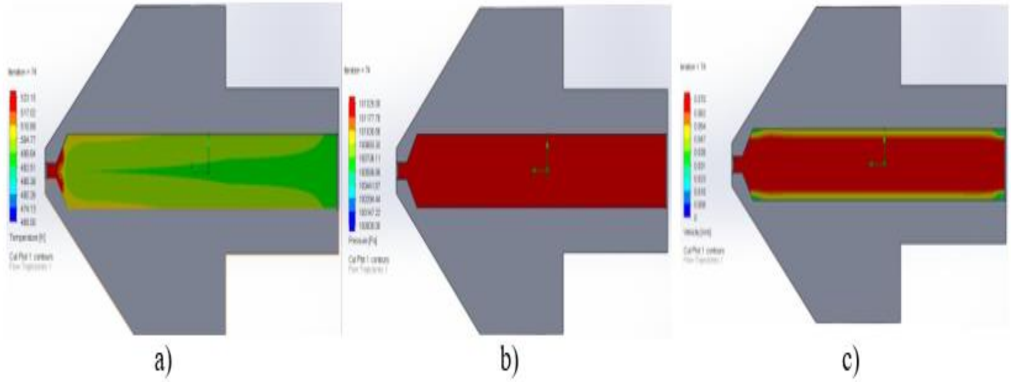

a) b) c)

Fig. 8*Cut plot of design B (1200 angle and 0.4 mm diameter) showing fluid pressure, temperature and velocity, respectively*

TABLE V*. Parameter Values For Case 1 (Design B)*

Case 1	Zone	Pressure, Pa	Velocity, m/s	Temperature, °C
B	1	101325	0.04-0.07	219.36-231.62
	2	101325	0.07	231.62-250.00
	3	101325	0.07	250

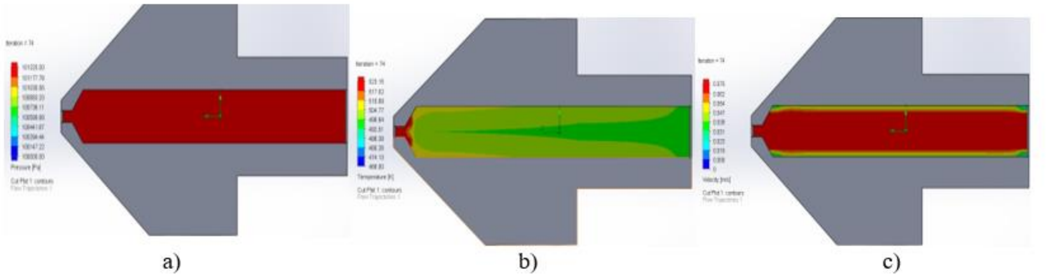
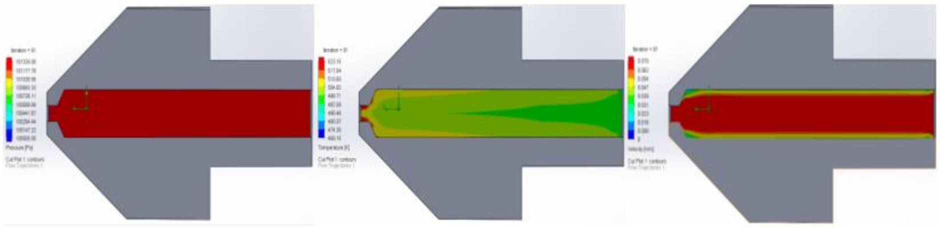

a) b) c)

Fig. 9 *Cut plot of design C (1200 angle and 0.4 mm diameter) showing fluid pressure, temperature and velocity, respectively*

TABLE VI. *Parameter Values For Case 2 (Design C)*

Case 2	Zone	Pressure, Pa	Velocity, m/s	Temperature, °C
C	1	101325	0.04-0.07	219.36-231.62
	2	101325	0.07	231.62-250.00
	3	101325	0.07	250.00



a) b) c)

Fig. 10*Cut plot of design D (1200 angle and 0.6 mm diameter) showing fluid pressure, temperature and velocity, respectively*

TABLE VII. *Parameter Values For Case 2 (Design D)*

Case 2	Zone	Pressure, Pa	Velocity, m/s	Temperature, °C
D	1	101325	0.04-0.07	219.44-231.67
	2	101325	0.07	237.78-243.89
	3	101325	0.07	243.89-250.00

The assist in selecting which design is the best, Pugh concept selection matrix was utilised, as shown in Table VIII.

TABLE VIII. *Pugh Selection Matrix*

		Pugh Concept Selection Matrix	A	B	C	D
Selection Criteria	Nozzle	Angle	+	++	++	++
		Diameter	+	+	+	-
		Material	+	+	+	+
	Functionality	Specific Material	+	+	+	+
		Clogging Problem	-	++	++	-
		TOTAL ++	0	2	2	1
		TOTAL +	4	3	3	2
		TOTAL --	0	0	0	0
		TOTAL -	1	0	0	2
		TOTAL SCORE	3	7	7	2

The matrix indicates that the favourable designs are Design B and C.

4. Conclusion

From the simulation results, the following can be concluded. The extruded liquid flow depends on the internal die angle and diameter geometry since the difference in the geometries affects the flow characteristics within the nozzle. The nozzle 120o angle with 0.4 mm circular diameter is found to be a functional geometry in delivering optimum extrusion process which produce an acceptable pressure drop for a quality flow. The brass was found to be effective material for extruding carbon fibre reinforced polymer as it provides stable temperature profile in the nozzle. It is important the temperature distribution and convergence is consistent with the speed of the liquid flow.

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