

Fabrication of Extrudate Filaments from Waste Polyethylene Terephthalate Plastics for 3D Printers

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Abstract— The use of 3D printers for manufacturing processes comes with the challenge of filament replacement for subsequent processes. This aforementioned including the environmental problems posed by plastics wastes formed the basis for the current work which is focused on design and construction of a simple single extruder for the production of filaments from waste polyethylene terephthalate (PET) plastics for rapid prototyping machines and 3D printers. Three Band heaters were used to melt the PET plastics and a screw was used to move the melted PET plastics longitudinally along the barrel. The screw is consisted of three zones namely feed zone, compression zone and metering zone. The temperature of the band heaters is controlled by a Digital temperature controller. This paper describes the design, fabrication and testing of a filament extruder. A 2mm die was used to extrude the filament to 1.75 mm. The performance of the system was quantified through relevant tests and the findings reported. When the barrel and die assembly are at 200°C, melting begins to occur and at 230°C, the extrudate begins to appear at the metering zone. The energy efficiency of the system was found out to be 75.2%.

Keywords— 3D printer, Design, Extruder, Filament, Polyethylene terephthalate

1 INTRODUCTION

Most of the 3D printers are based on the fused deposition, which uses mostly Acrylonitrile Butadiene Styrene (ABS) and Poly lactic Acid (PLA) as the printer material. A screw extruder is a mechanical device which consists of screw conveyor which has a variable pitch and increasing core diameter rotating inside a heated cylindrical chamber. The increase in pressure due to decrease in volume causes the input material to be conveyed along the length of the rotating screw. The input material is melted as it moves through the barrel and later forced out through the extrusion head. The extrusion head has a nozzle with the orifice shaped according to required extrudate geometry. A screw extruder can be used to ensure produce filaments for 3D printers. The extruder of the 3D printer uses a wired filament of diameter 1.75mm or 3mm for printing. Most of the manufacturing units, companies, colleges who have the 3D printer in-house are dependent on 3rd party supplier, and need to buy the 3D printer filament from these suppliers (Smith, 1978).

Considering the fact that there are several methods in which materials are extruded (Ugboya et al., 2019) modeled and fabricated a single screw extruder for melting and mixing of different categories of polymer. In other to eliminate some of the challenges encountered with existing extruders, a heating element was embedded in the screw including a thermostat to regulate and limit the amount of heat in the barrel. Considering the production rate, (Abebe et al., 2020) designed an automated integrated shredder and extrusion machine on a small-scale use with an efficiency of 80% and a capacity of 20.4kg of plastic blocks finished per hour, a working capacity of up to three cycles per minutes and a rate of production of 180 products per hour. The machine parts were simulated using CATIA, ANSYS and FESTO.

Hosseini *et al.* (2012) investigated various process parameters by friction stir extrusion such as transverse speed rate and rotational speed of the die on the microstructure and physical properties of the extrudate by employing inherent heating due to friction and extensive deformation of plastic.

For the design and development of extruder for plastics of different types (Dubashi *et al.*, 2005), in their work on extrusion as a process of making 3D printing filament, stated that liquid plastic is forced through an extrusion die and is formed into thin long strand of plastic. Also, (Proscher, 2012) in his work to extrude the plastic filament manufacturing for 3D-printer at large, which comprises of fabrication of a low case style extruder unit, stated that it comprises of the purchased CAD – software assisted together with the electronic fabrication of a first-generation extruder unit. Hence, the application of the universal parts to a reasonable extent in order to minimize the manufacturing cost is a unit target. The other target is the generation of unwavering extrusion process that has the capacity to recycle slashed plastic milk bottles.

This current work intends to design, construct and test a 3D printer filament making machine for small manufacturing units and colleges at low cost. The machine would be made from readily available materials sourced out from the local market, and the extruded filaments will be made from waste PET plastic. The filaments produced will be air-cooled and will be collected through a collection unit.

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Section C- MECHANICAL ENGINEERING & RELATED PHYSICAL SCIENCES

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2 METHODOLOGY

2.1 DESIGN ANALYSIS AND CALCULATION

The plastic filament extruder has a dimension of 1218.99 mm x 311.39 mm x 466.18 mm (see Fig. 2). Its major components are constructed from locally sourced materials. which are the major extruder components. It is powered by 500 W electric motor with a rotating speed of 1350 rpm.

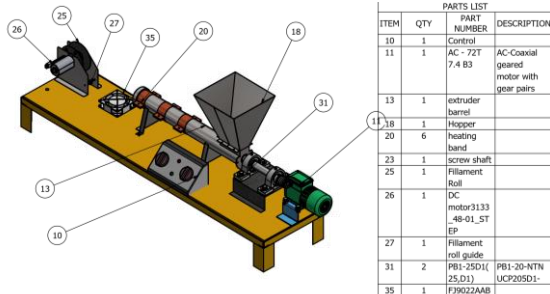


Fig. 1: Single screw extruder showing (1) part heaters, (2) extrusion barrel, (3) screw, (4) die, (5) hopper, (6) bearings, (7) filament extractor, (8) cooling fans, (9) filament roll, (10) filament roll guide, (11) AC geared motor, (12) DC geared motor, (13) control unit.

Plastic pellets are fed into the machine through the feed hopper and conveyed by the screw as it rotates along the barrel, to the die where it is discharged as filament. The hopper is a rectangular cross-sectioned reversed frustum with a height of 160 mm. The upper and the lower rectangular dimensions are 200 mm by 205 mm and 85 mm by 45 mm respectively. The horizontal extrusion barrel mounted on a triangular frame is a cylindrical structure made from a mild steel pipe of 36 mm internal diameter, thickness of 6 mm and length of 400 mm. This extrusion barrel has a 34 mm outer diameter screw/auger inside it that rotates to convey the plastic pellets from the inlet point at the hopper towards the die. The screw pitch, constant flight angle and channel width are 30mm, 26.7 ° and 24 mm respectively. The barrel transfers heat to the conveyed pellets from a three 1500 W, 220 V heater band clamped on it. The barrel discharges the molten pellets through the die which is screwed in at the exit end of the system away from the hopper. The die is made of 360 brass with 2 mm hole (orifice) which is the diameter of the extruded plastic filament.

The plastic filament extruder was designed based on the consideration of design for the barrel, design for the gear, design for the shaft, and design for the nozzle.

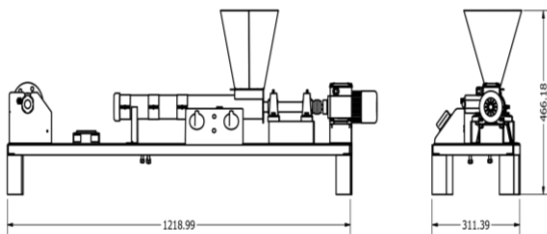


Fig. 2: Schematic of the filament extruder showing the various components

2.2 DESIGN OF THE BARREL

The barrel of the filament Extruder was design using the following parameters: Length of barrel, L=525 mm, Internal diameter, d=35 mm, External diameter, D=60 mm. The volume V_b of the barrel was determined to be 0.002m³ as proposed by (Khurmi and Gupta, 2005) in equation (1).

$$V_b = A_b L_b \tag{1}$$

where A_b is the area of the barrel = 0.05002044 m² and L_b is the barrel length = 0.4 m.

2.3 DETERMINATION OF CAPACITY OF THE EXTRUSION CONVEYOR

The capacity of the horizontal acting auger conveyor was calculated using the equation given by (Khurmi and Gupta, 2005) as shown in equation (2).

$$Q = 60n\phi\pi\gamma(D^2 - d^2)\frac{\pi}{4} \tag{2}$$

where;

Q= capacity of the screw conveyor in the barrel, t/h; bulk density of conveyed material, 300 kg/m³; n = number of screw rotation (assume 500 rpm); ϕ = factor induced for horizontal conveyor, 1; p= conveyor pitch, 0.05 m; D = pitch diameter of conveyor, 0.112 m, and d= shaft

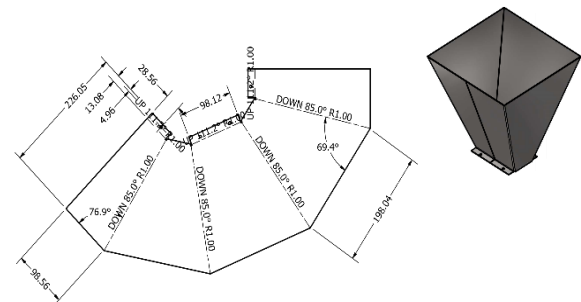


Fig. 3: Schematic diagrams of the Hopper

diameter, 0.03 m.

2.4 HOPPER VOLUME CALCULATIONS

The hopper was made from mild steel sheet metal and was designed as wedged shaped hopper. There are no specifications for hopper design. A truncated rectangular pyramid hopper was adopted (see Fig. 3).

Volume of the pyramid

$$V = \frac{1}{3}(A_1 + A_2 + \sqrt{A_1 A_2})h$$

Where, A_1 = area of top base

A_2 = area of bottom base

h = Height of bottom pyramid from(A_1 to A_2)

$$A_1 = 39,029.76 \text{ mm}^2$$

$$A_2 = 2,802.3 \text{ mm}^2$$

$$V = 2788512.63 \text{ mm}^3 \cong 2.7885 \text{ m}^3$$

2.5 DESIGN OF SCREW / AUGER

A horizontal screw conveyor or auger (Fig. 4) was designed and partially tapered with a constant pitch of 30mm. The extruder screw is divided into three sections, namely; feed section, compression section and metering section. The feed section which has a uniform channel width collects the solids PET from the hopper into the extruder. The PET solids are further mixed together and compressed into the compression section of the screw. The metering section is where the PET is melted and stabilized to a uniform temperature and composition. According to (Campbell, 2003), the following were the assumptions for the screw calculations; (i) flow is developed fully, (ii) channels of flow are filled completely, (iii) absence of slip at boundary surfaces, (iv) no flow leakage over the flight tips, (v) all channel corners are square, (vi) flow is Newtonian and isothermal, and (vii) channel dimensions are constant.

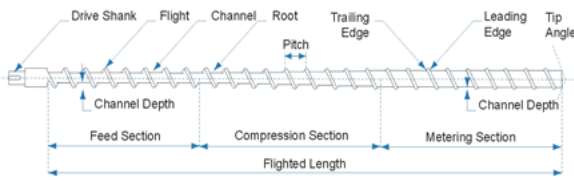


Fig. 4: Schematic of extruder screw

The geometry of the extruder screw (see Fig. 4) which includes the screw pitch, flight width, channel width, channel depth and pitch angle was designed using the equations provided by (Potente et al., 1994). Equations (3) to (9) were used to compute the relationship between the outer screw diameter and the distance between the axis of a flight screw; intermeshing angle (α), flight angle (β), screw pitch (t), angle of pitch (ϕ_s), channels width (b_{max}) and depth (h_{max}).

$$\frac{a}{D_s} \leq \frac{\sqrt{2}}{2} \tag{3}$$

$$\alpha = 2 \cos^{-1} \frac{a}{D_s} \tag{4}$$

$$\beta = \frac{\pi}{i} - \alpha \tag{5}$$

$$t = \frac{2\pi l_{kn}}{\delta j_{kn}} \tag{6}$$

$$\phi_s = \tan^{-1} \frac{t}{\pi D_s} \tag{7}$$

$$b_{max} = t \cos \phi_s - \epsilon_{max} \tag{8}$$

$$h_{max} = D_s - a \tag{9}$$

where, l_{kn} = 28 mm right-handed standard screw, δ = 1.57 radians, j_{kn} = standard screw element = 2, and a = distance between axis of flight (mm).

The dimensions of the extruder screw with a total length of 895 mm are presented in Table 1.

2.6 FLOW ANALYSIS OF THE EXTRUDER

The overall flow of pellets in the extruder is given as; Overall or total flow = Rotational or drag flow – pressure flow – leak flow $\tag{10}$

The leak flow is negligible because it is assumed that flow velocity is zero at the clearance between the barrel wall and outer diameter of the screw (Campbell, 2003). Therefore,

$$\text{Total mass flow} = \text{Mass drag (rotational flow)} - \text{mass pressure flow} \tag{11}$$

Table 1. Dimensions of extruder screw

Diameter (D)	50 mm		
Flighted Length	500 mm (10D)		
Feed Section Length	225 mm (4.5D)		
Compression Section Length	200 mm (4D)		
Metering Section Length	75 mm (1.5D)		
Compression Ratio	3		
Constant Screw Pitch (Flight lead)	50 mm (1D)		
Channel Depth Feed Section	7.5 mm (0.15D)		
Channel Depth Metering Section	3.5 mm (0.07D)		
Channel Width	2.5 mm (0.05D)		
Flight Width	5 mm (0.1D)		
Flight Angle	17.65°		
Screw Tip Angle	120°		
Flight to Root Radius	Feed Section	Compression Section	Metering Section
Leading Edge Radius	7.5 mm	7.5 - 3.5 mm	2.5 mm
Trailing Edge Radius	5 mm	5-2 mm	2 mm

According to Campbell (2003), the mass drag (rotational flow), Q_{md} was determined as 15.6 kg/h from equation (10).

$$Q_{md} = \frac{\rho_m V_{bz} W H_m}{2} \tag{12}$$

where; ρ_m = melt density of resin at 250 °C (960 kg/m³); V_{bz} = z component of the screw velocity at the barrel wall gotten from equation (11) as 0.058 m/s according to (Campbell, 2003)

$$V_{bz} = \pi N D_b \cos \theta \tag{13}$$

Where N is the screw rotational speed in rev/s (1.08 rev/s that is 65 rpm)

Also, the mass pressure flow, Q_{mp} was determined as 1.71kg/hr. from equation (14).

$$Q_{mp} = \frac{\rho_m W H^3}{12\eta} \frac{\partial z}{\partial z} \tag{14}$$

where;

η = Shear viscosity of molten resin polymer at average channel temperature (2000Ns/m²)

$\frac{\partial P}{\partial z}$ = Pressure gradient in the z direction channel (1.8 MN/m² per m) (Campbell, 2003)

The total mass flow rate of the extruder, Q_{mt} was determined as 13.89kg/hr. from equation (15).

$$Q_{mt} = Q_{md} - Q_{mp} \tag{15}$$

Q_{mt} is also the throughput capacity (TP), of the extruder. The throughput of the extruder was also alternatively determined as 13.89 kg/hr. from equation (16).

$$TP = \frac{60\pi}{4} (D_s^2 - D_c^2) L_s N \phi \rho_m \tag{16}$$

Where ϕ is the degree of pellet fill (0.875).

The Volumetric flow rate, Q_t of the extruder was determined as 0.000446 m³/s using equation (17), (18) and (19) (Campbell, 2003)

$$Q_t = Q_d - Q_p \tag{17}$$

$$Q_d = \frac{P V_{bz} W H_m}{2} \tag{18}$$

$$Q_p = \frac{PWH^3}{12\eta} \frac{\partial p}{\partial z} \quad (19)$$

where Q_d and Q_p are volumetric drag flow and pressure flow, respectively in m^3/s .

The maximum pressure, P_{max} in the extruder was determined as 4.3 MN/m^2 using equation (20) as proposed by (Campbell, 2003).

$$P_{max} = \frac{6\pi D_s L_m N \eta}{H^2 \tan \theta} \quad (20)$$

2.7 DETERMINATION OF THE MATERIAL HOLD UP/ VOLUME CAPACITY OF THE EXTRUDER

The equation for evaluating the hold up of materials in the barrel of a screw extruder was proposed by (Khurmi and Gupta, 2005) and it was used to evaluate the material hold up in the extruder barrel as $0.0000149m^3$ as expressed in equation (21).

$$V_m = \varphi V_{total} \quad (21)$$

where, V_m is the material hold up in m^3
 φ is the degree of fill (87.5%)

V_{total} is the reaction volume of the extruder which is the difference between the barrel volume and volume of the screw/auger.

2.8 DESIGN OF DIE

The die (see fig. 5.) was designed using the following criteria. The proposed die must provide a uniform rate of flow of the materials through its exit gap, constantly provide a uniform melt temperature over the whole of the exit gap, produce a melt that has the same shear history for all parts of the exit gap. The failure to meet up with these criteria can possibly result to poor thickness distributed in the extrudate, poor dimensional inaccuracy, inappropriate melt stiffness, die swell behavior and poor appearance.

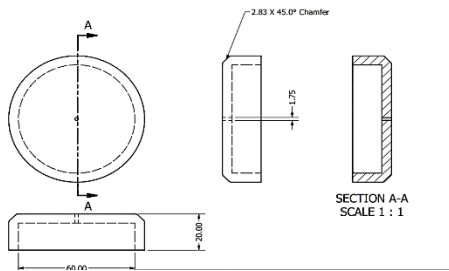


Fig. 5: Schematic diagram of the Filament Extruder die

Determination of die pressure: According to (Campbell, 2003), $P_d < 0.5P_{max}$. Where P_d is the die pressure i.e. P_d is usually less than half of the maximum barrel pressure. Therefore, the die pressure, P_d was determined to be 1.81 MN/m^2 .

Determination of die heater power: The heating of the die was achieved using an electrical heating element (heater band) clamped on the outer part of the body with thermocouple deeply embedded and controlled by PID type temperature controller. The heating power of the die, P_h was determined as 1500 W using equation (22) as proposed by (Dynisco, 2007).

$$P_h = \frac{w c_{sp} (T_2 - T_1)}{t} \quad (22)$$

Where w = die weight (0.42 kg); C_{sp} = specific heat capacity of die material ($375 \text{ J/kg}^\circ\text{C}$ for brass); $T_2 - T_1$ = temperature rise ($250^\circ\text{C} - 20^\circ\text{C}$); and t = time required to heat the die. However, three heaters, 1500 W each, were used so that heating time can be significantly reduced. One was attached to the die while the other was attached to the barrel.

2.9 SELECTION OF PRIME MOVER

The power required by the screw, P_s conveyor was calculated from the expression given by (Khurmi and Gupta, 2005) as 0.00097 KW from equation (23).

$$P_s = 0.7355 C L_s Q_{mt} \quad (23)$$

where C is the constant coefficient of conveyed material usually taken to be 0.3 .

A 220 V , 500 W , $1:10$ geared AC motor was used in this work.

2.10 EXTRUDATE COOLING

For the formed thermoplastic to retain its shape, heat must be removed from it. The amount of heat contained in the polymer melt is used to determine the quantity of heat to be removed and cooling needed. In this work, cooling was achieved by using a 12 V DC electric fan and the amount of heat removed from the extrudate was determined to be 1.75 kW as proposed by (John Goff and Tony Whelan, 2007) using equation (24).

$$H_c = Q_{mt} C_p (T_m - T_f) \quad (24)$$

where H_c is the heat content of the polymer in watts (W); C_p is the polymer specific heat capacity ($1970 \text{ J/kg}^\circ\text{C}$); T_m is the melt temperature (250°C) and T_f is the final temperature (20°C)

2.11 CONSTRUCTION

The filament extruder (Fig. 6) assembly is made up of a cylindrical barrel housing a screw or auger and connected to a series of band heaters. The screw is supported at both ends by two ball bearings and connected to a geared electric motor. The shredded waste PET plastics (Fig. 7a) are gravity fed continuously into the system from the hopper. As the motor drives the auger, it then pushes the resin pellets towards the outlet point of the machine. The heat from the heating band is evenly distributed using asbestos ribbon which ensures the PET plastics soften and melt prior to being pushed continuously through a die. This action ensures the fabrication of continuous filament strand with the die geometry (Fig. 7b). Air cooling system was used to ensure solidification of the extrudate. The filament is pulled out of the die and rolled using a 12 V DC motor.

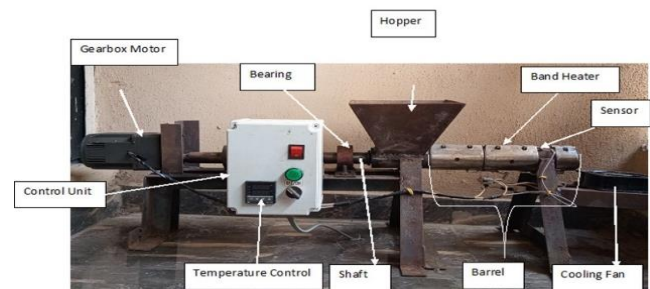


Fig. 6: Filament extruder

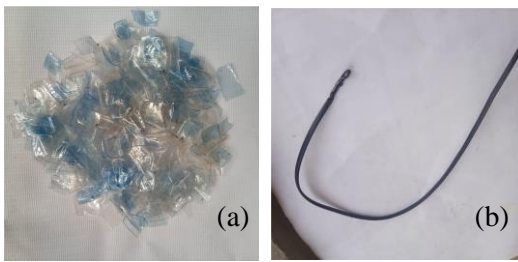


Fig. 7. (a) Shredded waste PET plastics and (b) filament fabricated using the single screw extruder

3 RESULTS AND DISCUSSION

The following tests conducted on the single screw extruder, namely; temperature evaluation at the three zones and cooling test of the extruded filament.

3.1 TEMPERATURE EVALUATION AT THE THREE ZONES

Fig. 8 shows the results obtained from the temperature evaluation at the three zones. It was observed that after 30 minutes of heating, the temperature remained constant as the thermostat has a heating limit of 230 °C.

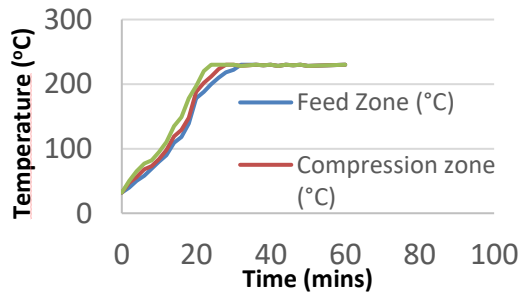


Fig. 8: Graphical results showing Temperature across the zones versus time curve

3.2 COOLING TEST OF EXTRUDATE

Fig. 9 shows the results obtained from the cooling test on the extrudate. During cooling from 230°C to 130°C, the extrudates began to solidify after 20 minutes of fan cooling. Further cooling for additional 30 minutes reduces the temperature of the extrudate to a room temperature about 31°C.

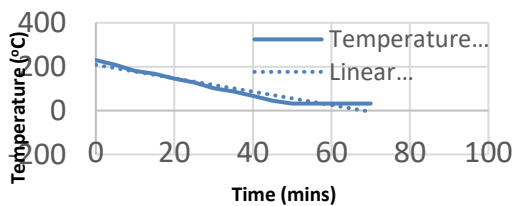


Fig. 9: Graphical results showing Cooling temperature against time

3.3 EFFICIENCY OF THE SYSTEM

In the case of an extruder, the energy used for useful work (E_u) is the energy used for material melting and forming through the die which is given by equation 25:

$$E_u = E_{in} - E_{losses} \quad (25)$$

where E_{in} is the total energy supplied to the extruder while E_{losses} is the total amount of energy wasted with no involvement in any useful work. E_{in} is the electrical energy supplied to the various devices such as drive motor, barrel and die heaters, motor cooling fan, barrel

cooling fans, water pump and instruments in the control panel. E_{losses} include energy losses that occur in devices and other mechanical or functional systems such as transmission, forced and natural cooling. The motor and barrel/die heaters consume over 90 % of the total energy supplied and account for the greatest energy losses. It is a major challenge in extrusion system to recover energy loss because it is largely dissipated into air or water. The energy efficiency of the extruder ($\eta_{extruder}$) is given by:

$$\eta_{extruder} = \frac{E_{in} - E_{losses}}{E_{in}} \times 100\% \quad (26)$$

$$\eta_{extruder} = \frac{\text{work output}}{\text{work input}} \times 100\% \quad (27)$$

where work output corresponds to the weight

$$\text{Work output (1000cm}^3\text{)} = 253\text{g} = 0.253\text{kg}$$

$$\text{Work input} = 348\text{g} = 0.348\text{kg}$$

$$\eta_{extruder} = \frac{0.253}{0.348} \times 100\% = 75.2\%$$

4 CONCLUSION

The single extruder for the fabrication of filaments from waste polyethylene terephthalate (PET) plastics for 3D printers and rapid prototyping machines was designed and constructed with an energy efficiency of 75.2%. The results obtained from the temperature evaluation at the three zones shows that the temperature distribution across the zones is uniform; this could be ascribed to the high thermal conductivity of the metal used (Mild steel). With the barrel and die assembly at 200°C, melting begins to occur and at 230°C, the extrudate begins to appear at the metering zone. The result for the thermal cooling shows that the cooling rate is directly proportional to the temperature of the surroundings.

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