Chapter 04. Manufacturing of CFF/PLA composites

4.1 Preamble

Additive manufacturing/3D printing of composite materials is now in the research stage. Components with composite materials have been attempted to manufacture by 3D printing technology by following methods.

a. *Extrude composite filament for 3D printing using the FDM technique*

   Filaments used in the FDM technique are made of composite material. The fibers, usually in particulate form are mixed with the matrix material during the process of formation of filament. The composite filament is used melted and deposited layer by layer to form the component. This method gives more flexibility to the complexity and fiber orientation inside the component to be manufactured.

b. *Sandwich method*

   The method utilizes a combination of 3D printing and hot compression moulding. Predesigned layers of thermoplastic are first manufactured by 3D printing. Fibers are then placed between the layers in the required orientation. The sandwich materials are hot pressed at temperatures below the crystalline temperature till the layers fuse and the components are obtained

c. *Fiber laying during 3D printing*

   In this method, after each layer of printing, fibers are laid on the printed part, and on it, the next layer is printed. The process is repeated to get the desired shape and number of layers.

In the present study, the approach for the first two methods has been attempted and the outcome in the form of characteristics has been compared.

4.2 Composite CFF/PLA Filament Extrusion

The existing composite filaments usually are in particulate form, so they are extruded from the conventional filament extruders. In the case of short fibers, the conventional filament extruders tend to get choked and also result in uneven distribution of fiber in the filaments. To overcome the hurdle a composite filament extruder was designed and fabricated. The schematic of the same is shown in Figure 4-1. The notable features added in the design are the heater placement, clearance between screw and barrel, the nozzle design, and the hot water bath.

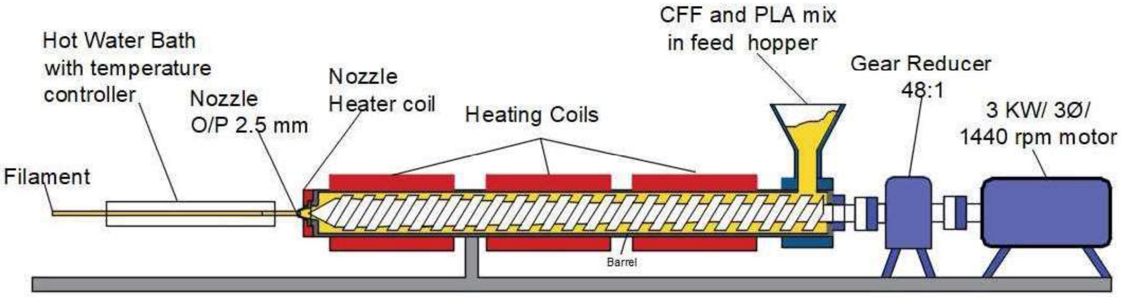

Figure 4-1 Schematic of indigenously designed and fabricated composite filament extruder.

The design and fabrication of the filament extruder are discussed in the subsequent section.

4.2.1 Composite Filament Extruder

The existing composite filaments usually have fibers in particulate form, so they are convenient to be extruded from the conventional filament extruders. In the case of short fibers, the conventional filament extruders tend to get choked and also result in uneven distribution of fiber in the filaments. To overcome the hurdle a composite filament extruder is designed and fabricated.

The working of a conventional filament extruder is illustrated in Figure 4-1. The material is forced through a nozzle die of the required dimension and cross-section to produce components with uniform cross-section. The constituent materials are fed into the hopper. After passing through the heated barrel, the material melts. The screw helps in the mixing and movement of the material ahead in the barrel. It also helps to create pressure to push the material out of the shaping die.

In the present study, a single screw extruder is chosen because of its ease of manufacturability and simple design compared to multi-screw extruders. Also, a single extruder provides comparatively less shear between the barrel's inner wall and pallets and gives a very high throughput. The main components to be designed or selected are an extruder screw, barrel, heaters for heating and melting the material, a motor-drive system for rotating the screw, and a control system for the heaters and motor speed. Single screw extruders can have a single-stage or multistage compression.

In the present design, multistage compression has been achieved by varying the root diameter of the screw. Multistage screws have three zones: the feed zone, the compression zone, and the metering zone (Womer et al., 2017). Figure 4-2 shows the various zones of multistage extruder screws.

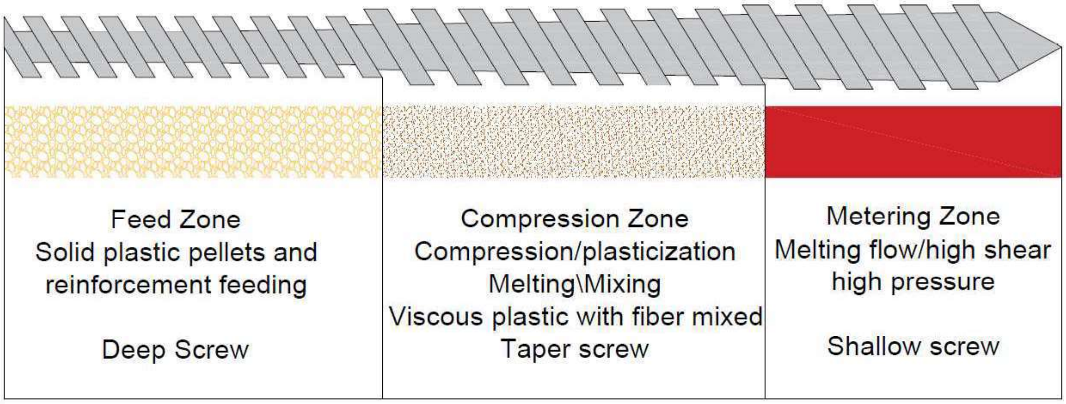

Figure 4-2 Various zones of multistage extruder screws.

In the feed, the section mixture is preheated and compacted to be fed forward. The compression zone, however, is the zone where the matrix in the mixture starts melting and is packed further. As a result, the material is mixed homogeneously and pushed through the nozzle in the required quantity. The pressure needed to pump out of the material from the die is generated in this zone. In the case of polymers, the pressure required is proportional to the Melt Flow Index (MFI). For each zone, separate heater bands propose precise temperature control in each zone. A longer length of the screw is considered to prolong the mixing of the matrix and fiber material. The cause-and-effect diagram shown in Figure 4-3, showcases various input parameters and the outputs which are affected by them.

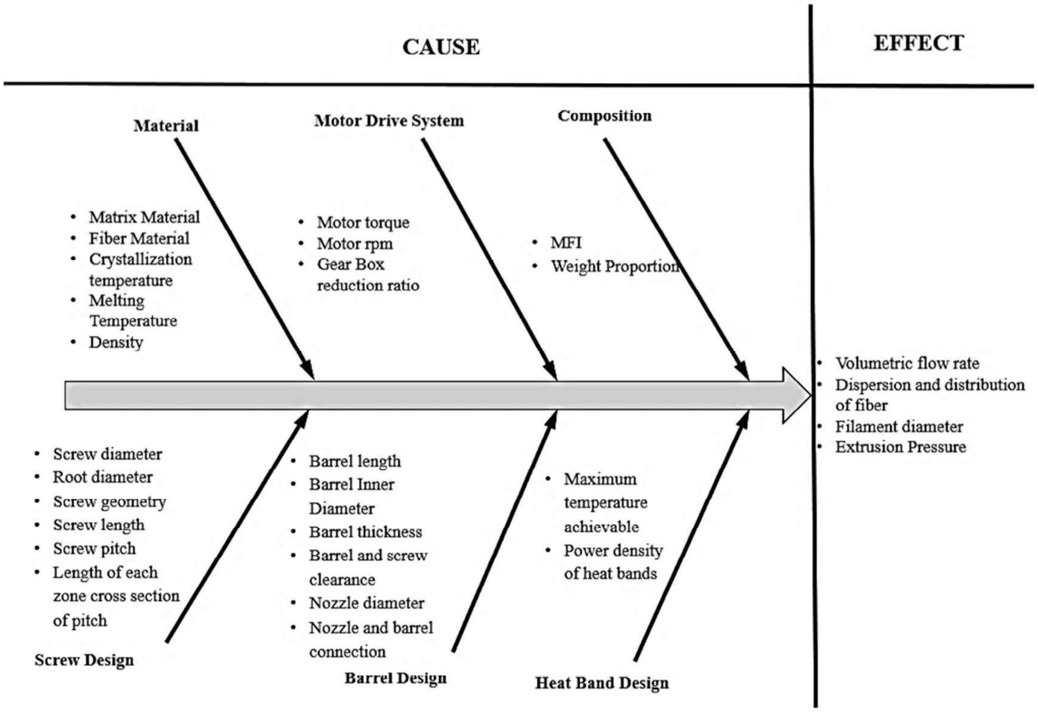

Figure 4-3 Fish Bone Diagram for Cause and Effect in composite filament extruder.

As per the cause and effect diagram, the following input parameters are to be controlled and designed to get the desirable outputs.

a. Screw design,
  - Screw diameter
  - Root diameter
  - Screw geometry
  - Screw length
  - Screw pitch
  - Length of each zone cross-section of pitch,

b. Barrel design
  - Barrel length
  - Barrel Inner Diameter
  - Barrel thickness
  - Barrel and screw clearance (minimum and maximum)

c. Nozzle assembly
  - Nozzle diameter
  - Nozzle and barrel connection

d. Heater band
  - Maximum temperature achievable
  - Heat capacity of heater bands
  - The power density of heat bands

e. Hopper design
  - Minimum breath of hopper mouth for free-flowing of bulk solid

f. Motor sizing
  - Motor torque
  - Motor rpm

These output parameters influenced by various input parameters are

- The volumetric flow rate of extruded filament
- Dispersion and distribution of fiber in the matrix material (Mixing efficacy)
- Filament diameter
- Extrusion pressure

4.2.2 Design of Filament Extruder

The nomenclature used in the presented design is shown in Figure 4-4. An industrial extruder utilizes the L/D ratio in the range of 23:1 to 30:1 (Womer, 2000). In the design proposed, the L/D ratio is assumed to be 23:1 while the diameter of the screw (D) is considered 30 mm. These assumptions are based on the availability of the components locally. The material to be selected for the screw and barrel should have very high dimensional stability at elevated temperatures to avoid expansion of the screw or barrel, which usually results in stalling. The material for screws in the present research is selected as nitrided steel. Nitrided steel tends to have better dimensional stability than alloy steel, even at elevated temperatures of 500 °C. (Whelan and Dunning, 1988).

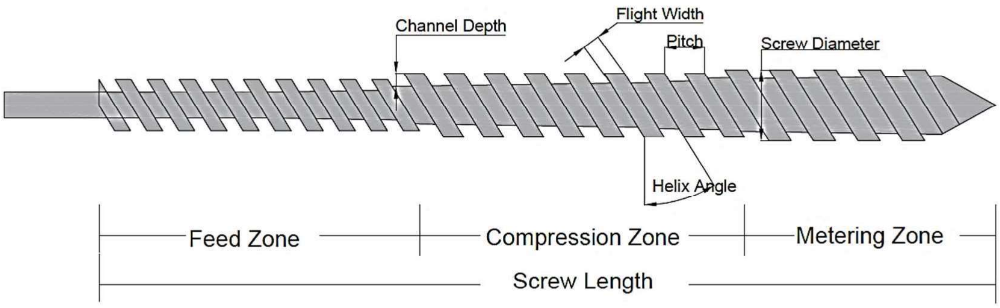

Figure 4-4 Nomenclature of extruder screw geometry.

The compression ratio of the screw (CR) is defined as the ratio of the feed zone's channel depth to the metering zone's channel depth. Here it is assumed as 4:1.

4.2.2.1 Extruder Screw Design

The design steps and calculations of the screw of the extruder are described in Table 4-1

Table 4-1 Calculations for the single screw composite filament extruder.

Parameters	**Design Expression**	**Values**
Screw geometry (Wankhade and Bahaley, 2018)		
Diameter of Screw	Assumed D =30	30 mm
L/D ratio	L/D = 23:1	23:1
No of channels/start	m	1
Pitch	t = D	30 mm
Helix angle at the driving end	$\emptyset = \tan^{-1}\frac{t}{\pi D}$	17.65°
Ridge/Flight width	$e \geq 0.12 D$	4 mm
Screw lengths (Campbell et al., 2013)		
Length of feeding zone L1	0.217 L	150 mm
Length of compression zone L2	0.348 L	240 mm
Length of metering zone L3	0.435 L	300 mm
Channel depth h		
Channel depth in the feed zone:		
Maximum depth	0.2 x D	6 mm
Granule size	d_g	3 mm
As per the granule size	2 x d_g	6 mm
Compression ratio	CR	4
Channel depth in the metering zone		
Minimum depth	0.05 x D	1.5 mm
Flight clearance δ	0.03 x D/2	0.5 mm

4.2.2.2 Barrel Design

Wankhade and Bahaley (Wankhade and Bahaley, 2018) have given elaborative steps to calculate barrel geometry shown in Table 4-2.

Table 4-2 Barrel Design.

Parameters	**Design Expression**	**Values**
Barrel dimensions		
Barrel ID D_b	$D + 2\,\delta$	31 mm
Corrected Flight clearance δ	$(D_b - D)/2$	0.875 mm

4.2.2.3 Heater Band

Wankhade et al,(Wankhade and Bahaley, 2018) have given elaborative steps to calculate the heater band shown in Table 4-3. For the calculation purpose the material with higher density i.e. PLA has been considered (Feuerbach et al., 2019; Y. Tao et al., 2019)

Table 4-3 Heater band.

Parameters	**Design Expression**	**Values**
Heater Band		
The density of PLA	ρ	1.28 g/cm^3
The volume of barrel V	$\pi L\, r^2$	4.88 x 10^5 mm^3
Melting power needed	$W = \rho\, V\, C\, \Delta T$ (C is the heat capacity of PLA)	65.362 kJ
Nos of heat band One heater band for each heat zone	n	3
Length of heater band	L_h	150 mm
Power density in heat bands ψ	$= \dfrac{\text{melting power needed}}{\pi \text{ x barrel OD x length of heater x n}}$	543 kJ/m^2
The heat band selected has the following specifications.		
ID of band	$= D_{bo}$	85 mm
Heater wattage	W	1 kW
Material of heating element		Mica

4.2.2.4 Hopper

The opening of the hopper is a parameter that regulates the input flow of material in the extruder. The minimum opening of the hopper is taken as $5 \text{ x } d_g \sqrt{3} = 26$ mm (Wankhade and Bahaley, 2018).

Figure 4-5 shows the arrangement of various components of the composite filament extruder assembly as per the calculated design. First, the motor drives the screw inside the barrel through the gearbox. Next, the volume between the screw and barrel is heated using heating coils. Finally, the plastic granules and fibers mixture are fed through the hopper near the H1 heating coil.

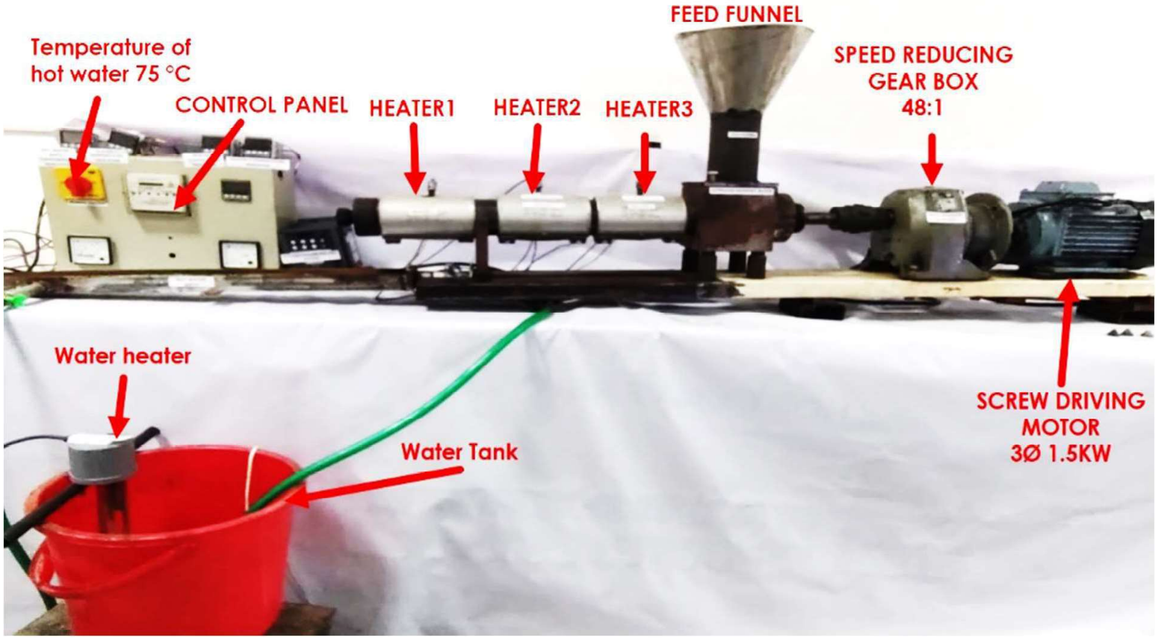

Figure 4-5 Composite filament extruder assembly manufactured.

4.2.2.5 Volumetric flow rate of the extruder

Rauwendaal and Rauwendaal, 2018 presented how to determine the volumetric flow rate Q for single screw extruders.

Volumetric flow rate Q is a mix of three flows

a. Drag flow
b. Pressure flow
c. Filtration flow

$$Q = \left(\frac{\alpha K}{K + \gamma + \beta}\right)\eta \tag{1}$$

Where,

Drag flow coefficient = α
Pressure flow coefficient = β
Filtration flow coefficient = γ

Screw speed = η

Geometrical constant = K

Drag flow coefficient α

$$\alpha = \frac{\pi * m * D * h * \left(\frac{t}{m} - e\right) * (\cos \phi)^2}{2} \tag{2}$$

Pressure flow coefficient = β

$$\beta = \frac{m * h^3 * (\frac{t}{m} - e) \sin \phi \cos \phi}{12. L} \tag{3}$$

Filtration flow coefficient = γ

$$\gamma = \frac{\pi^2 * D^2 * \delta^3 * \tan \phi}{10 * e * L} \tag{4}$$

Screw speed = η

Rated rpm of motor = 1450 rpm

Reduction using gearbox = 1:48

Factor of safety = 2

Geometrical constant = K

Outer diameter of nozzle d0 = D - 2*h

The inner diameter of nozzle d1 = 2 mm (same as the diameter of filament required for 3D printing)

Length of nozzle Ln = 6 mm

Assuming it as a cylindrical section

Geometrical constant

$$K = \frac{\pi\, d1^4}{128 * Ln} \tag{5}$$

From equation no (1), Volumetric flow rate Q

$$Q = (\frac{\alpha K}{K + \gamma + \beta})\eta$$

Length of the filament produced per sec Lp

$$Lp = \frac{Q}{\pi * d1^2/4} \tag{6}$$

4.2.2.6 Motor Capacity

Following are the steps to decide the motor capacity:

Maximum Temperature Tm = Melting temperature of PLA + 45 = 155+45 = 200 ̊C

Minimum temperature T0 = Ambient temperature = 35 ̊C

Volumetric flow rate Q = 55.9 mm^3/s

Required power to rotate the screw P

$$P = \rho * Q * C * (Tm - T0) \tag{7}$$

$$P = 7.5 \text{ kW}$$

The power required to rotate the screw at 15 rpm is 7.5 kW. Assuming, Factor of safety is 2, Speed reduction in the gearbox is 48:1, Transmission efficiency = 95%

Motor power Pm(ABB, 2018)

$$Pm = \frac{P * \text{Factor of safety}}{\text{speed reduction in gearbox x transmission efficiency}} \tag{8}$$

$$Pm = 0.33 \text{ kW}$$

Rated motor power PR = Pm * 1.73 / η_m *PF* (9)

Assuming mechanical efficiency η_m as 85%, Power Factor for motor PF as 0.81

Rated Motor power *PR* = Pm*1.73 / η_m PF

= 0.83 kW

The motor with a rated power of 1 kW was considered.

4.2.2.7 Extruder Nozzle Design

The nozzle is an important component of the extruder. The function of the nozzle is to ensure that the filament extruded is of the required size. Figure 4-6 shows the photographs of nozzles of hole diameters 1.5 mm, 2 mm and 2.5 mm. Figure 4-7 is the dimension drawing of the nozzle with variation in hole diameter. Figure 4-8 is the drawing of the nozzle holder nut while Figure 4-9 is the drawing of the connector between the nozzle and the barrel. The connector is secured on the barrel using 8 numbers of M10 Allen bolts. Figure 4-10 shows the exploded view of the assembly. These components are the major modifications compared to the standard filament extruder. The modifications are carried out considering the CFF of short lengths. The assembly will help in ease of cleaning and replacement in case of choking due to fibers of uneven diameters.

(a) (b) (c)

Figure 4-6 Extruder nozzles of hole diameter (a) 2 mm (b) 1.5 mm, and (c) 2.5 mm.

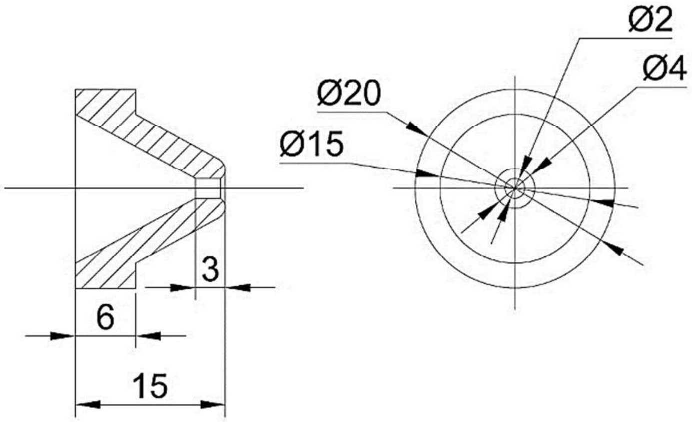

Figure 4-7 Extruder nozzle (all dimensions are in mm).

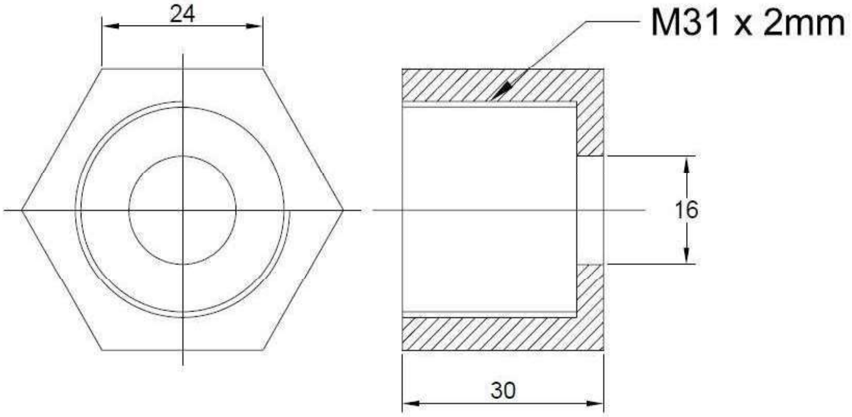

Figure 4-8 Nozzle holder Nut (all dimensions are in mm).

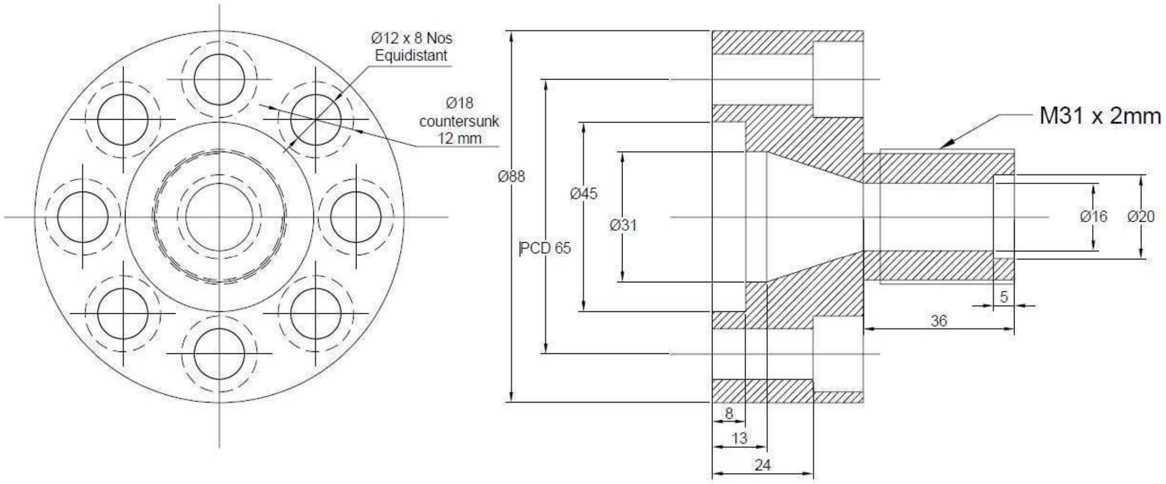

Figure 4-9 Nozzle barrel connector (all dimensions are in mm).

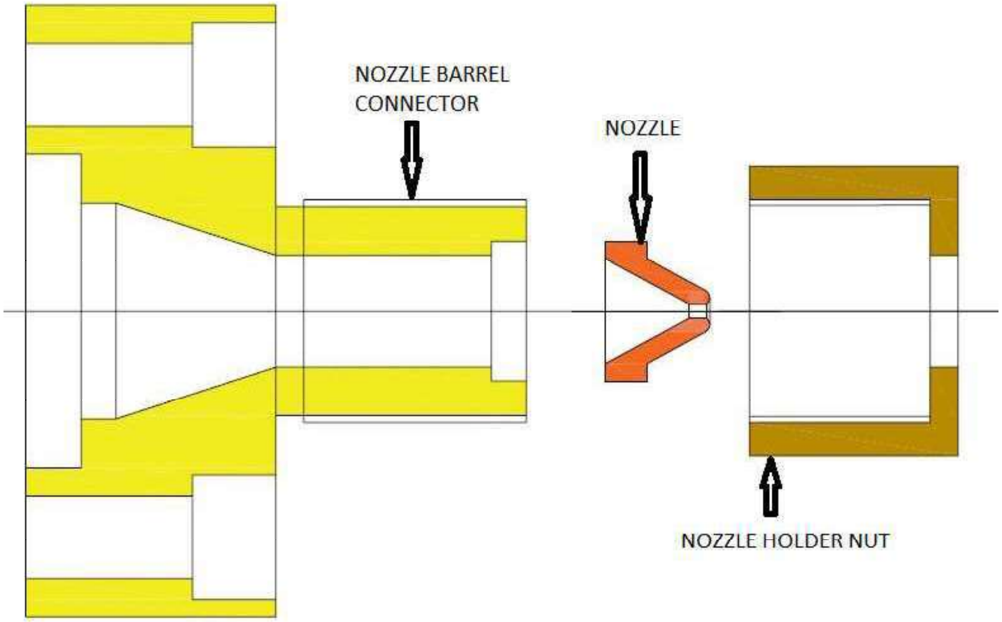

Figure 4-10 Exploded View of nozzle barrel connection.

4.2.2.8 Hot water bath

The hot water bath is incorporated for controlled cooling of the CFF/PLA filament after it is extruded from the extruder nozzle. The water is kept at 75°C which is 5°C above the glass transition temperature of PLA. The hot water bath ensures gradual and controlled cooling of the extruded filament. This prevents rapid cooling which leads to brittleness of the extruded filament. Figure 4-11 shows the arrangement of the hot water bath system.

The hot water bath has

a. *Water tank*

To store the water for circulation and provide a location to heat the water.

b. *Temperature controlled water heater*

To heat the water at the required temperature.

c. *Water circulation pump*

For continuous circulation of hot water in the hot water tank

d. *Water flow controller*

The water flow controller is required to maintain the water level inside the hot water tank.

e. *Hot water tank*

The hot water tank provides the location to immerse and provide a gradual cooling system for the extruded filament

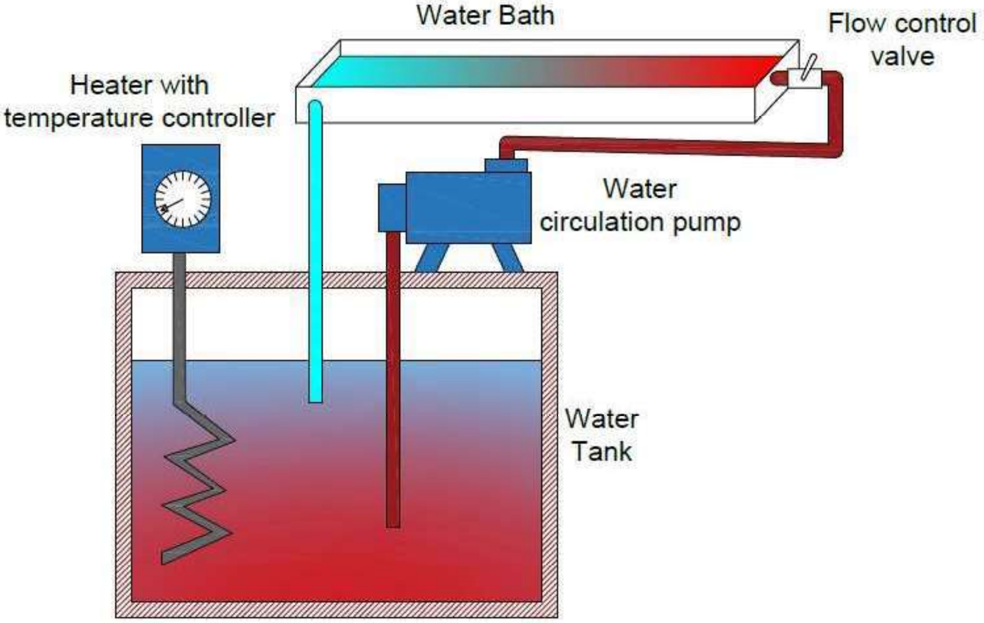

Figure 4-11 Hot water bath system.

4.2.2.9 Short fiber reinforced composite filament extruder assembly

Figure 4-12 shows the schematic of the short fiber reinforced composite filament extruder designed for extruding the CFF reinforced PLA filament for the study presented in this thesis.

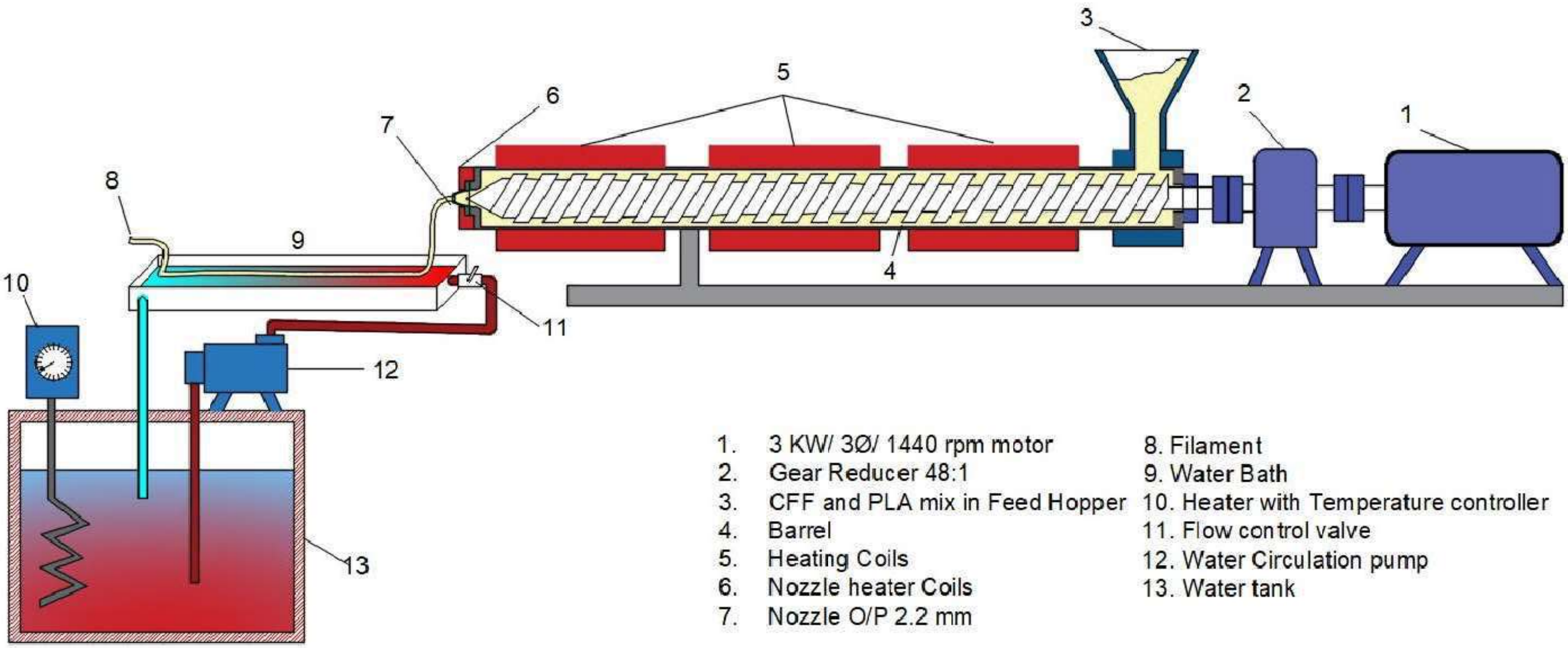

Figure 4-12 Short fiber reinforced composite filament extruder assembly.

4.2.3 Preparation of CFF/PLA filament Samples

Pilot experiments were conducted on the specially designed composite filament extruder. Various proportions of CFF/PLA were taken on a trial basis to obtain the tentative range of their weight percentage of them. After obtaining, satisfactory results, the range of weight percentage of CFF/PLA/TEC was obtained. It was obtained as shown in Table 4-4.

Table 4-4 Range of weight percentage of constituent materials.

Material	Weight %
PLA	90 – 96 %
CFF	2-4 %
TEC	2-4%

Also, the machine parameters, which included Heater temperatures, nozzle diameter, screw speed, water bath temperature, and hot water flow rate was obtained. For preparation of the samples Heater 1 temperature was 150 °C, Heater 2 temperature was 134 °C, Heater 3 temperature was 134 °C, nozzle diameter was 2 mm, screw speed was 25 rpm, and water bath temperature was 75 °C and hot water flow rate was maintained at 20 ltr/min. The PLA granules were baked at 80°C for 6 hours in an air oven. The CFF length was maintained between 1-3 mm. Considering the machine parameters constant, the design of experiments (DOE) was done using the Taguchi method. A three factor and three level DOE array was obtained, using Minitab software. Table 4-5 shows the factors and their levels while Table 4-6 indicates the DOE array.

Table 4-5 Factors and their levels for the Taguchi Method.

PLA gm	CFF gm	TEC gm
180	4	4
186	6	6
192	8	8

Table 4-6 Taguchi array L9 (3^3).

Expt. No	PLA gm	CFF gm	TEC gm
1	180	4	8
2	180	6	4
3	180	8	6
4	186	4	6
5	186	6	8
6	186	8	4

7	192	4	4
8	192	6	6
9	192	8	8

Attempts were done to prepare samples according to the Taguchi array obtained and the observations were noted. The observations are shown in Table 4-7.

Table 4-7 Observations from the experiments carried out according to the Taguchi array.

Expt. No	**PLA gm**	**CFF gm**	**TEC gm**	**Remarks**
1	180	4	8	The filament was very soft and we could not push it through the printer roller. The filament had a higher diameter (around 2.8 mm) because the presence of an excessive plasticizer caused the filament to blow up.
2	180	6	4	CFF distribution was random, in some places there were very few CFF while in other places they were densely present.
3	180	8	6	There was excessive choking due to excess CFF.
4	186	4	6	The filament was very soft and we could not push it through the printer roller. The filament got compressed between the rollers but later expanded and could not be pushed through the printer extruder.
5	186	6	8	CFF distribution was random, in some places, there were very few CFF while in other places they were densely present. There was excessive choking of the nozzle. The filament diameter was uneven. At places where CFF was dense the diameter was 2.2 mm while at places where it was scarce, it got blown to a diameter of 3.1 mm.
6	186	8	4	There was excessive choking of the nozzle.
7	192	4	4	The filament had a smooth surface and the diameter was even with a diameter varying between 2.2 – 2.24 mm. Also, the CFF was evenly distributed.
8	192	6	6	Excessive choking of the nozzle and also pinholes were observed.
9	192	8	8	There was excessive choking so the filament was not extruded.

The only proportions that gave desired results were the one proposed in experiment 7. Confirmatory experiments were carried out with the same proportion and repetitive results were obtained.

4.3 Sample preparation by sandwich method

To compare the filament sample properties with another method of manufacturing, samples are prepared by the sandwich method. The method utilizes a combination of 3D printing and hot compression moulding. The PLA strips were designed as per the standard size of 185mm x 20mm x 2mm in AutoCAD. The predesigned sheets of PLA are manufactured by 3D printing on an FDM printer. Manually alternate layers of PLA sheets and a layer of CFFs are then placed into specifically designed moulding equipment. The sandwich materials in the mould are hot pressed at temperatures below the crystalline temperature of PLA, till the layers fuse. The process is shown in Figure 4-13. The samples are compressed to a thickness of 5 mm in the specially designed mould. The assembly is then heated to the temperature of 210 °C for 15 minutes at the rate of 11°C/ min. The assembly is removed from between the heaters and it is allowed to cool below the glass transition temperature of PLA, i.e., 45 °C, before removing the sample from the mould.

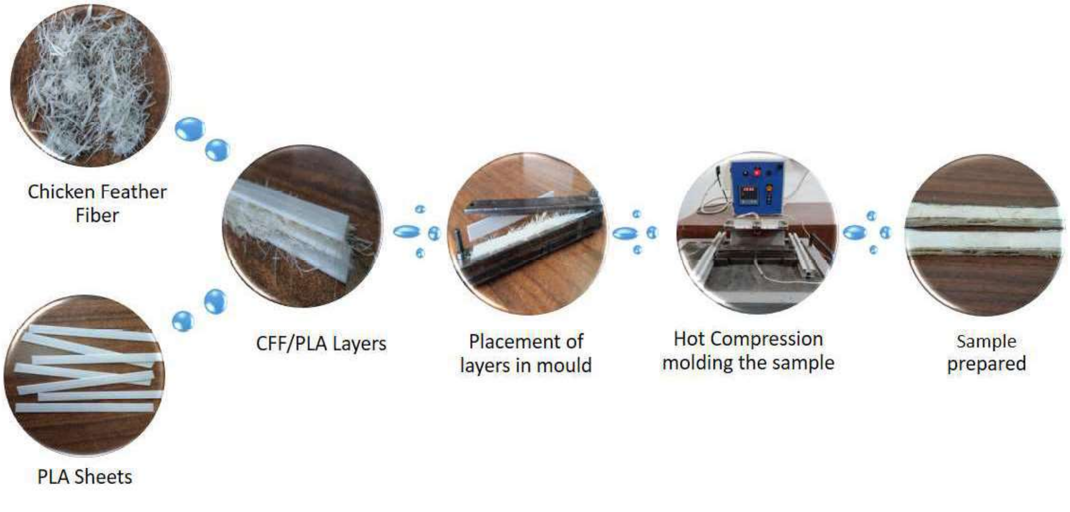

Figure 4-13 Process of preparing CFF/PLA samples using the sandwich method (Adil et al., 2023).

The PLA sheet utilized has a Melt Flow Index (MFI) of 6 g/10 min, a molecular weight of 20,000 g/mol, a melting point of 130°-180° C, and a density of 1.24 g/cm^3. The chicken feather fibres demonstrated a tensile strength of 23.9 g/tex, while the density is observed between 0.8 to 1.12 g/cc (Pradhan et al., 2020; Reddy and Yiqi Yang, 2007).