DESIGN & ANALYSIS REPORT

OF

DESIGN AND MANUFACTURING OF CONTINUOUS FIBER 3D PRINTER WITH CONTINUOUS FIBER FILAMENT

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Abstract

Composite part manufacturing is labor-intensive, costly, and needs to perform complex methods such as vacuum bagging. Because of these composite applications are limited to only the high-end aerospace industries. On the other hand, 3D printed thermoplastic parts are weak to be used as structural components.
Because of COVID-19 product industries are most affected compared to software industries. Virtual development of products becomes impossible because of the need of prototyping.

This problem can be solved by continuous fiber 3d printing. In this project, the solution is proposed to solve the above problems. By printing continuous carbon fiber embedded in nylon and using it in 3d printing, the strength part should be significantly increased. By achieving merely 35%-40% of fiber fraction printed parts could have strength comparable to steel.

1.Introduction:

The 3D Printing (Additive Manufacturing) Industry has experienced significant growth in the last few years, and it is predicted to bring revolution among the manufacturing industries for creating next-generation high-performance materials. Additive manufacturing primarily uses thermosetting plastic which is cheap but barely produces any strength at all.

In order to enhance the performance of the plastic composite, different reinforcement; for instance, carbon black, platelets, chopped fibers, polymer fibrils are mixed with thermoplastic matrix and then extruded together during printing. The performance of these composites significantly depends on the fiber orientation in the plastic and fiber volume fraction (FFV). However, they still show inferior mechanical performance compared to traditional fiber-reinforced composites. Therefore, to widen the application of 3D printed FMD technology for designing high-performance composites, is a need of the product industry. The technology available with this feature is known as continuous filament fabrication (CFF). In this project we are developing a CFF printer at very low cost so it can replace traditional composite manufacturing processes.

1.1. Problem Statement:

To reduce the cost of composite part manufacturing by vacuum bagging or molding process, we are designing and manufacturing continuous fiber 3d printers with continuous fiber filament.

1.2. Objectives:

- To manufacture continuous fiber filament with good surface finish and consistent diameter of ±0.05mm.
- To design a 3D printer that is compatible with printing the continuous fiber filament parts.
- To print the generative or topologically optimized part with a continuous fiber 3d printer.

Continuous fiber-reinforced composite materials are now used in a wide range of applications including aerospace, automotive, industrial, and sports goods. The materials normally contain a thermosetting polymer matrix (usually an epoxy or polyester resin) reinforced with carbon, glass, or aramid fibers. These materials have higher strength and stiffness per unit weight and often have lower finished component costs than the metals they replace.

2.Filament Properties Calculation:

The fiber-reinforced composite made by prepreg or vacuum bagging method has up to 60% of fiber volume fraction. However, such high fiber volume fraction may not work in 3d printing because porosity is generated by a gap between two diagonally adjacent filaments in print that need to be filled with thermoplastic material for good strength. We can observe in previous continuous fiber 3d printing a maximum of 40% of fiber fraction is achieved.

2.1. Tensile Strength and Modulus of Elasticity of filament

For the selection of fiber, a comparison between different fibers is done. From the below comparison, carbon fibers are clearly the stiffest and strongest fiber and also *fibers and mild steel* comparatively stronger than steel.

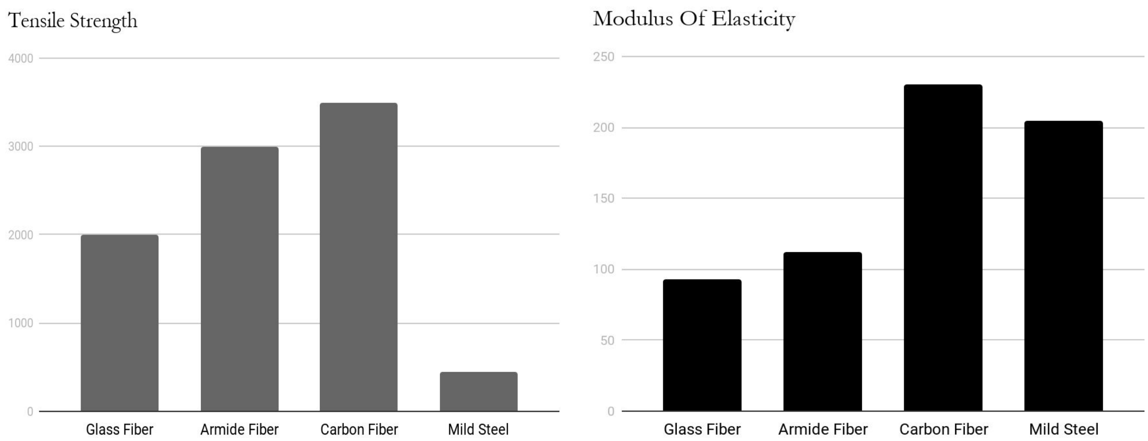

Fig1: Tensile strength (MPa) and modulus of elasticity (GPa) comparison between different

The properties of the composite can be calculated as follows.

$$P_c = FVF \times P_f + (1 - FVF) \times P_m$$

Where,

P_c = property of composite,

P_f =property of fiber,

P_m =property of the matrix,

FVF=Fiber volume fraction.

So, for 0.35 fiber volume fraction strength of carbon fiber is 1225 MPa, and the Modulus of elasticity is 80.5 GPa with neglecting the properties of the thermoplastic matrix which are very small compared to reinforcement.

2.2. The diameter of filament:

The thickness of filament for a particular fiber count (nk) and fiber volume fraction (FVF) is as follows.

Density of Carbon Fiber $\rho = 1930\ kg/m^3$.

Weight of 1k carbon fiber per unit length $\lambda = 66 \times 10^{-6}$ kg/m.

Fiber count = *nk (k=1000).*

So, Cross-sectional area of filament… $A = n \times \frac{\lambda}{\rho} \times \frac{1}{FVF}$

Hence, Diameter of Filament… $D = 2 \times \sqrt{A/\pi}$

Sr. no	Fiber Count	FVF	Diameter of Filament (mm)
1	1k	0.35	0.3527
2	1k	0.40	0.3300
3	3k	0.35	0.6108
4	3k	0.40	0.5715
5	6k	0.35	0.8639
6	6k	0.40	0.8083
7	12k	0.35	1.2217
8	12k	0.40	1.1431

Table 1: Diameter of filament for different fiber count and different fiber volume fractions.

From diameter calculation, 1k and 3k fiber count is suitable for good print quality which is achieved between 0.1mm to 0.6mm of print nozzle. Furthermore, we also need to consider the cost and availability of fiber. 1k carbon fiber cost is around 200$/kg which is 4 times high compared to 3k fiber which is 48$/kg.

From this analysis, we have selected Carbon Fiber reinforcement with 3k fiber count and 0.6mm diameter of a nozzle for printing.

3. Pultrusion:

Pultrusion is a process in which composite parts are manufactured by pulling of fibers that are impregnated with thermoplastic or thermosetting plastic with various methods. A general block diagram of the protrusion is shown below.

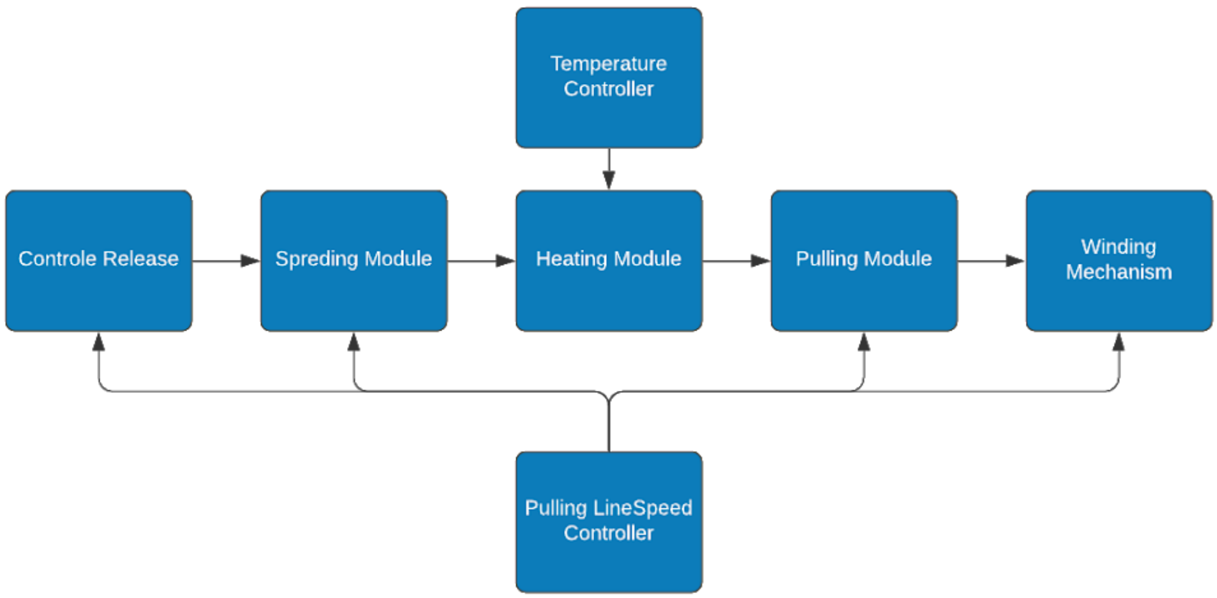

Fig. 2: Block diagram of the pultrusion process.

For the manufacturing of Continuous carbon fiber-nylon filament, we manufactured a Pulltruder which CF with nylon ensuring proper infusion and proportion. This mechanism is a combination of a Spreading module, heating module, pulling module, and winding module.

3.1 Pultrusion 1.0:

Design 1.0 is based on the extrusion process in 3D printing with additional protrusion of fibers.

3.1.1 CAD design:

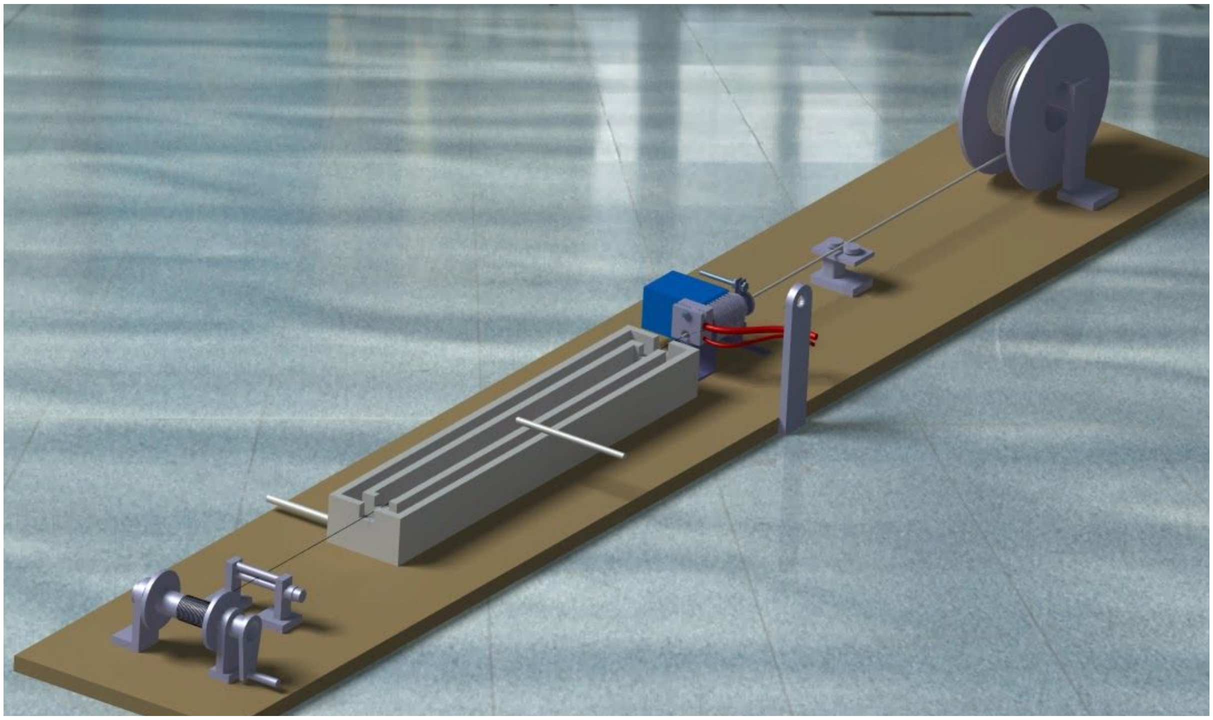

Fig.3: Complete pultrusion assembly.

In the above figure is a complete assembly of the first iteration of pultrusion. First, the fiber tow is placed on the left, passes through the heating nozzle. The heating element is nothing but 3d printing v6 nozzle with a hole at the end to pass the fiber as shown in fig below.

Thermoplast is passed by pushing filament of 1.75mm thermoplast from the rear end of the heating element similar to 3d printing. This coated filament is then passed through water to cool down the filament. This cooled down filament is then collected on a coil.

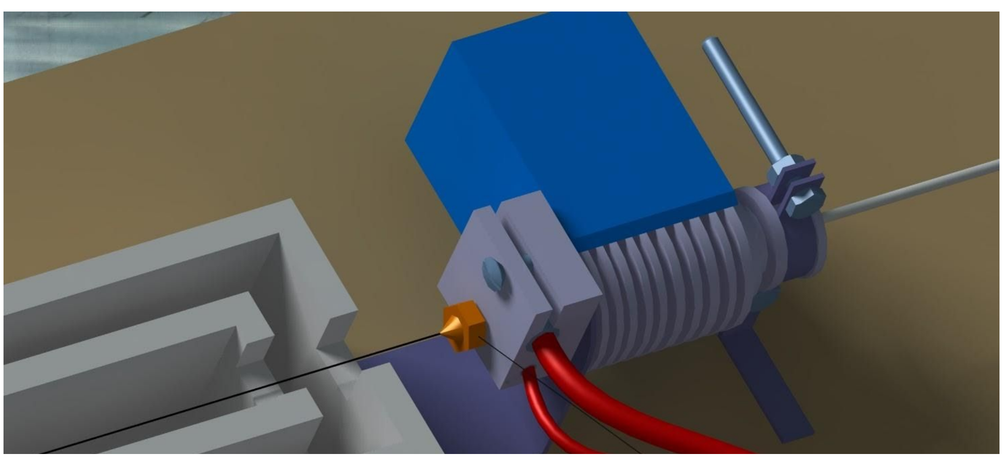

Fig 4: Heating module and fiber feeding system.

3.1.2 Prototype 1.0:

In this prototype the thermoplastic filament of PLA is fed by a feed mechanism. The rate of feed is adjusted manually through the motor controller. 12V supply is given to the heating cartridge.

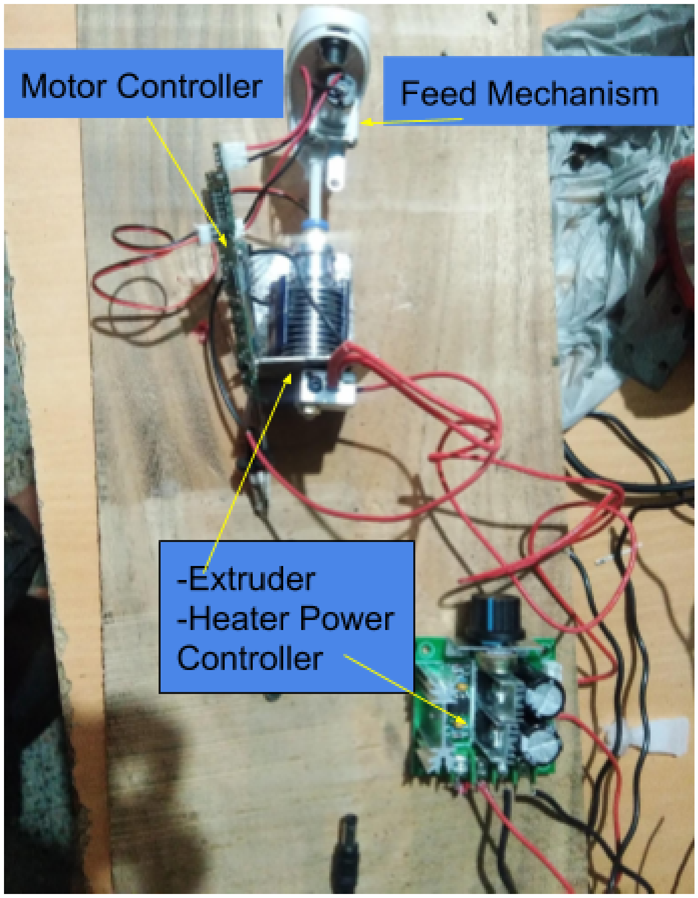

Fig 5: Pultrusion Design 1.0 Prototype.

3.1.3 Prototype 1.1

In this prototype spreading of the fibers is done by passing fibers through different holes, impregnating them in molten thermoplastic. Afterwards these fibers combined by passing through 0.7mm nozzle as shown in fig below.

Fig 6: Prototype 1.1

3.1.3 Results:

Fig 7: Prototype 1.0 filament

Fig 8: Prototype 1.1 filament

1. From prototype 1.0 only surface imprignation of filament is achieved.
2. Because of thermoplastic feed mechanism clogging was observed.
3. In prototype 1.1 complete impregnation of fibers is achieved.

4. Because of fiber separation by different holes fiber breakage occurred. These broken fibers become the reason for clogging further.

3.1.4. Conclusion:

1. There is a need for a spreading module which can spread fibers uniformly without breakage or distortion.
2. Thermoplastic flow must not be forced but it should flow under gravity to avoid fiber distortion.
3. Fiber should not have a sharp turn in molten nylon to avoid clogging as it was in design1.0.

3.2. Pultrusion Design 2.0:

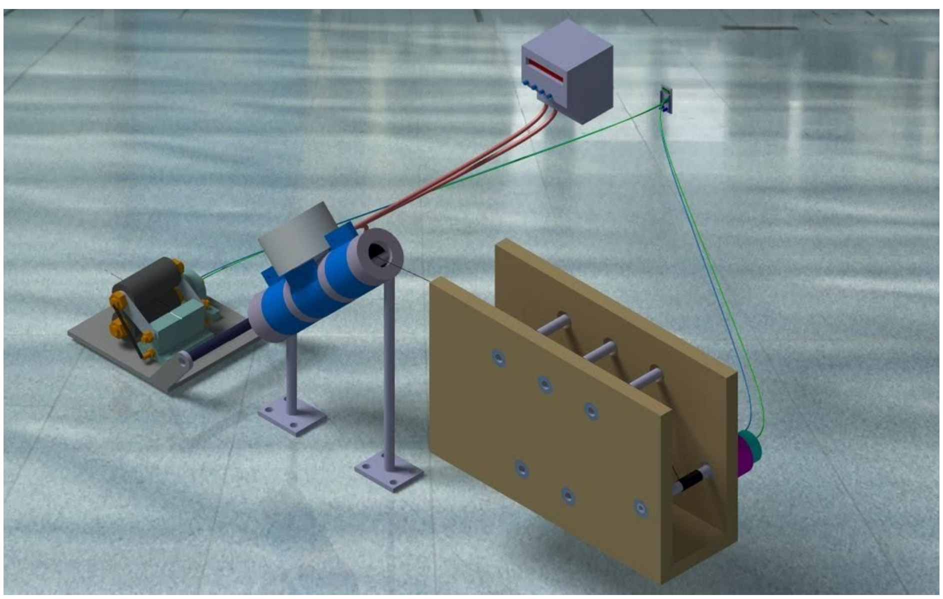

Fig 9: Pultrusion design 2.0

3.2.1. Spreading module:

To manufacture the filament of diameter 0.7mm from 3k CF, we use a spreading mechanism that spreads the 3k fibers of 2mm width to a width of 12mm. This is done via passing the 3k fibers under tension around 5 polished cylinders. These cylinders can rotate about their own axis and are mounted on the frame by using ball bearings as shown below.

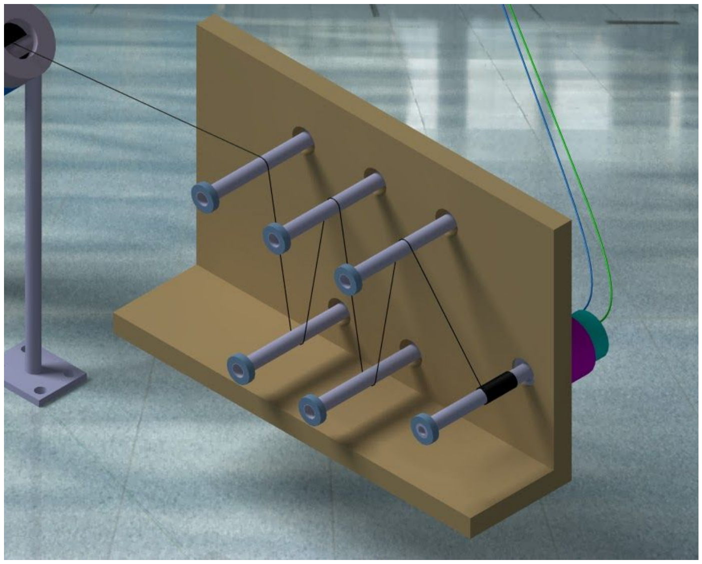

Fig 10: Spreading Module after removing a left section

In order to obtain the right number of cylinders and tension force to be applied, we carried out a number of iterations and selected 5 cylinders.

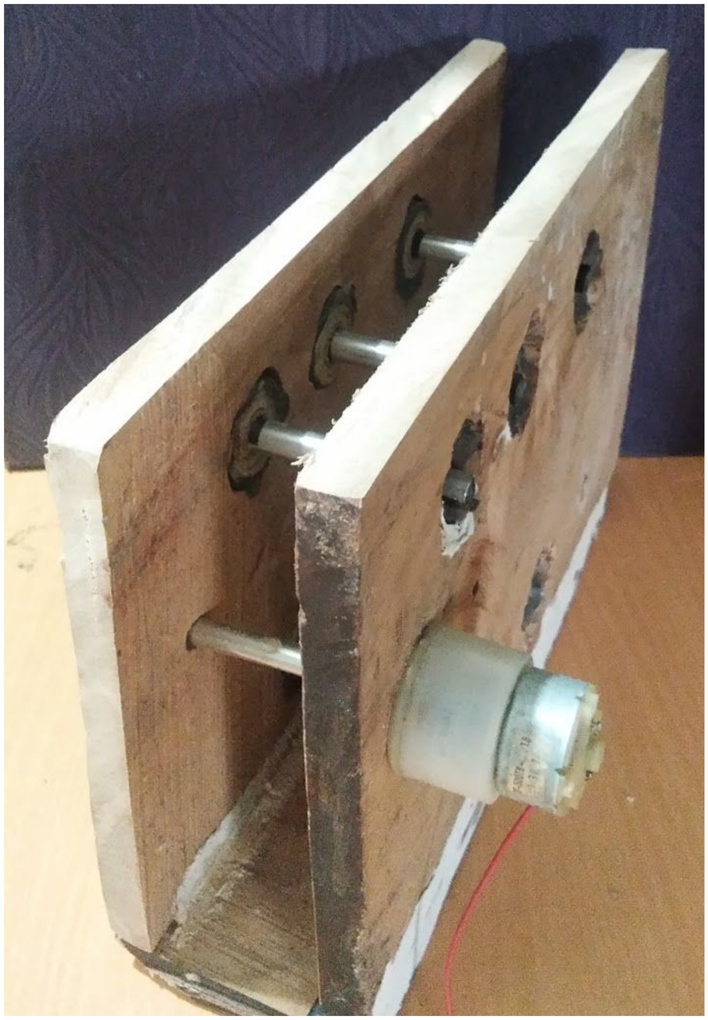

Fig 11: Spreading Module.

3.2.2. Heating module:

After the spreading of fibers, the strands are pulled through a container containing molten nylon. The spread strands enter the heating module from the right side and the coated filament is pulled out from the left side of a module. Nylon pellets are added from the upper portion of a module. The module has a heater that maintains a temperature of 280 ^{0}C through the pipe. This temperature is above the melting point of nylon.

Fig 12: Heating Module

To avoid the solidification of nylon, we did a thermal analysis of this pipe and ensured uniform temperature across the pipe. The control module is used to maintain the required temperature.

Given below are images of a prototype of the heating module.

Fig 13: Heating Module without insulation.

3.2.3. PID Temperature Controller.

For the temperature controller, we have used an Arduino UNO. For temperature measurement k-type thermocouple for which can measure temperature up to 1020^0C. This recorded temperature is displayed on 16×2 I2C display.

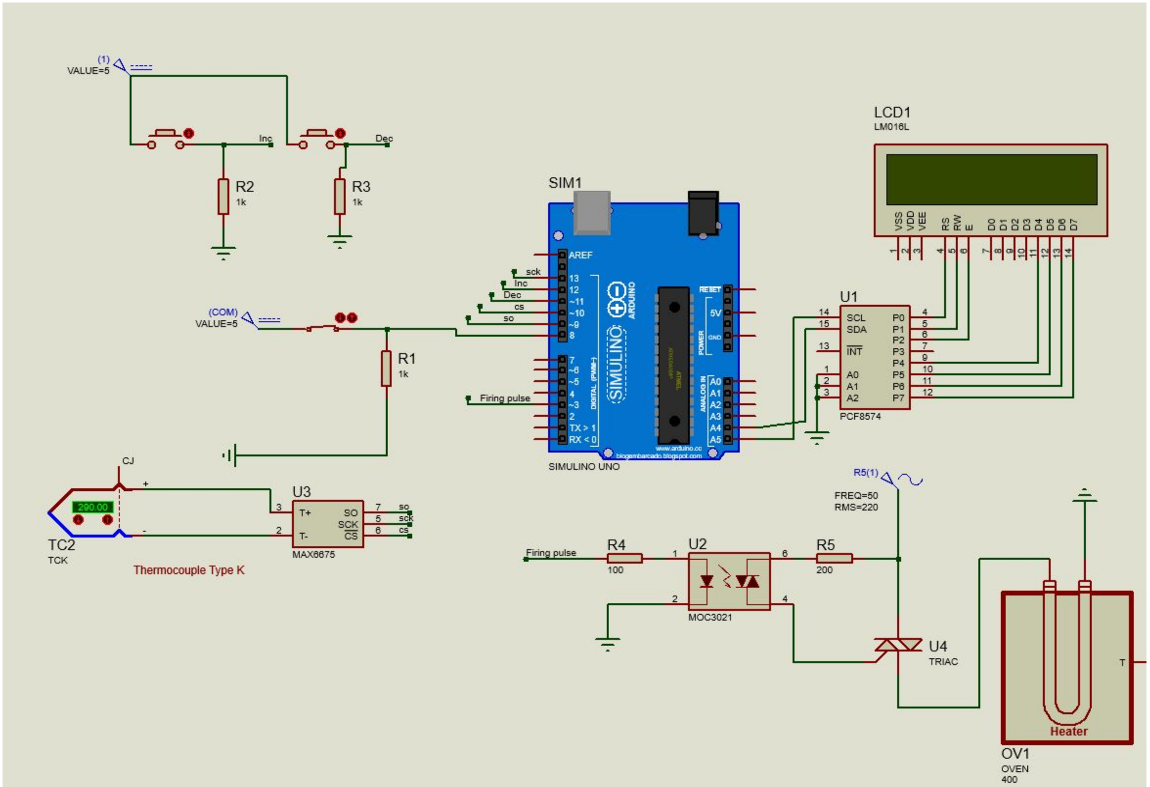

Fig 14: Temperature controller circuit diagram.

For controlling current flow TRIAC is used which is coupled with Arduino by Optocoupler MOC3021 for ensuring isolation of high voltage circuits from low voltage circuits.

The heating module is small and so it is prone to fluctuation in temperature if we use an ON/OFF type control system. For accurate control on temperature and to avoid overshoot of temperature PID controlling method is implemented. The tuning of PID is explained in the simulation chapter.

3.2.4. Pulling Module:

This module pulls the filament from previous modules and directs it to a spool. Filament passes between two drums which are rolled by a motor connected to one drum. The upper drum applies force on filament through spring action. These components are 3D printed.

Fig 15: Pulling mechanism by using rubber drums.

4. Simulation & Analysis:

Thermal analysis was done to ensure temperature fluctuation is not high throughout and it maintains the melting temperature of nylon in the heating system and 3d printing nozzle.

4.1 Heating system:

A heating system is used to heat up and melt the nylon. But this should be maintained between 290-350 degrees. If the temperature is lower nylon won’t melt and if it is higher it will start to fume. Hence thermal analysis is required for the same.

4.1.1 CAD of heating system:

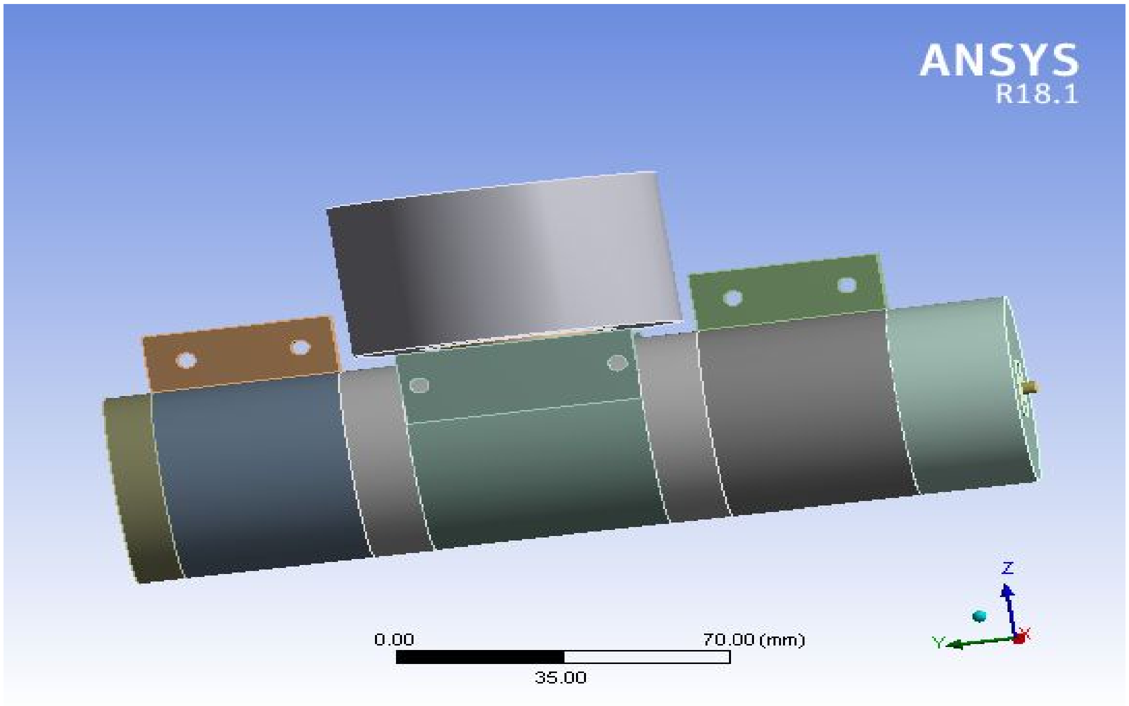

Fig 16: CAD of Heating System.

This heating system consists of three heaters that are clamped to a one-inch pipe which contains nylon to be melted. From the upper region nylon beads, then these beads are melted and the fibre is passed through it.

The pipe material is steel whereas the polymer inside is nylon.

4.1.2 Mesh:

The mesh used was a mix of hex and tetrahedron mesh. Mesh size used is 1mm.

Mesh quality check: quality check is done to ensure that the results obtained can be trusted.

ASPECT RATIO	1.9

SKEWNESS	0.75
No. OF ELEMENTS	50946
No. OF NODES	132556

Table 2: Mesh Specifications of Heating System.

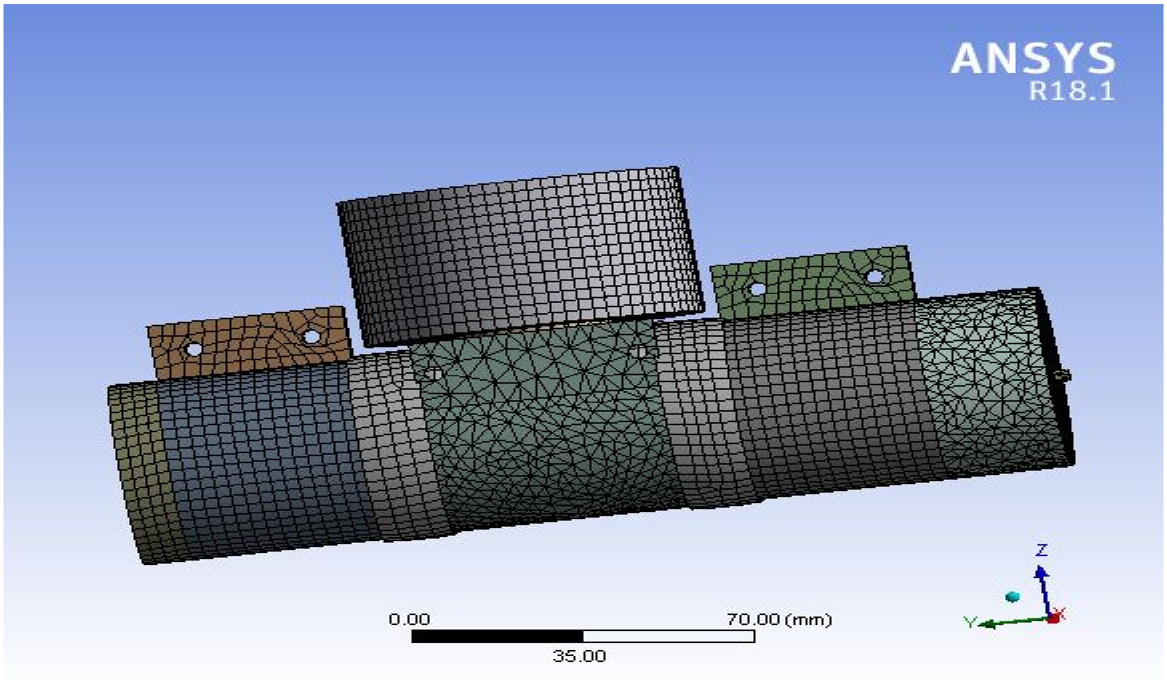

Fig 17: Mesh Illustration of Heating System.

4.1.3. Thermal loading conditions:

The three heaters heat up the pipe with a heat flux value of 9.5×10^{-5} $W.mm^{-2}$. Also, there are heat losses due to radiation with an emissivity of 0.8.

The upper portion is insulated so that no heat escapes through that region.

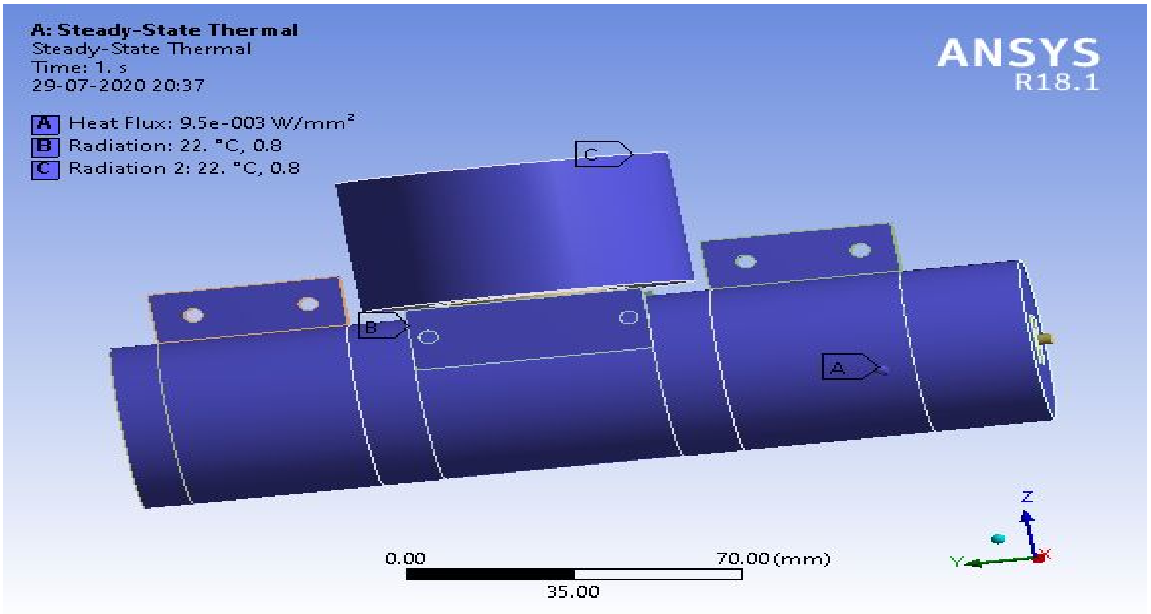

Fig 18: Thermal loading constraints.

4.1.4.Results:

The thermal gradient required for the pipe should be between 270-350.

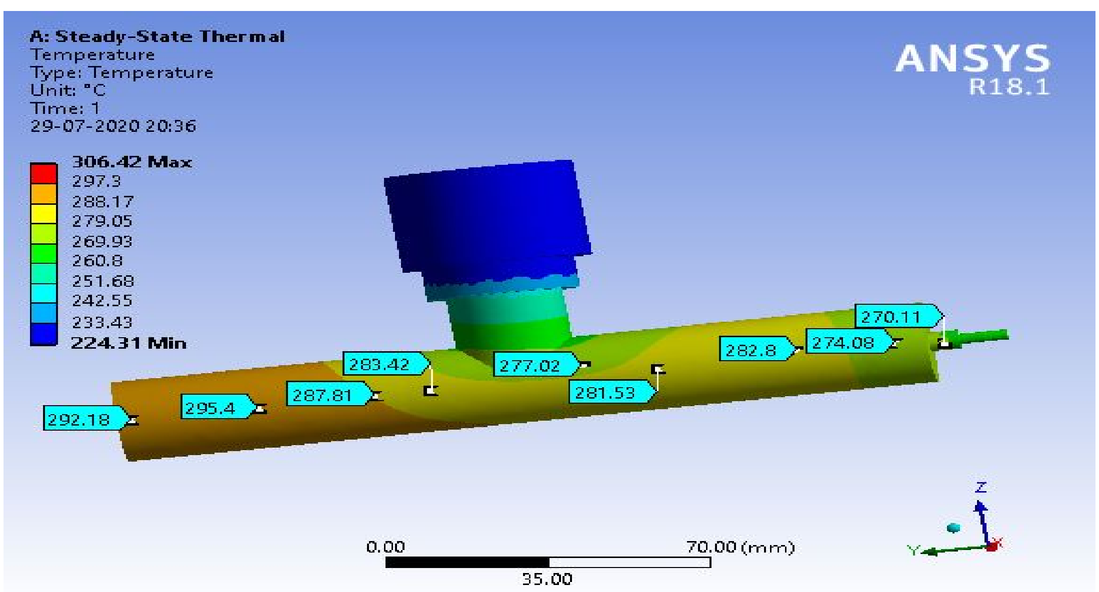

Fig 19: Temperature Gradient of Nylon.

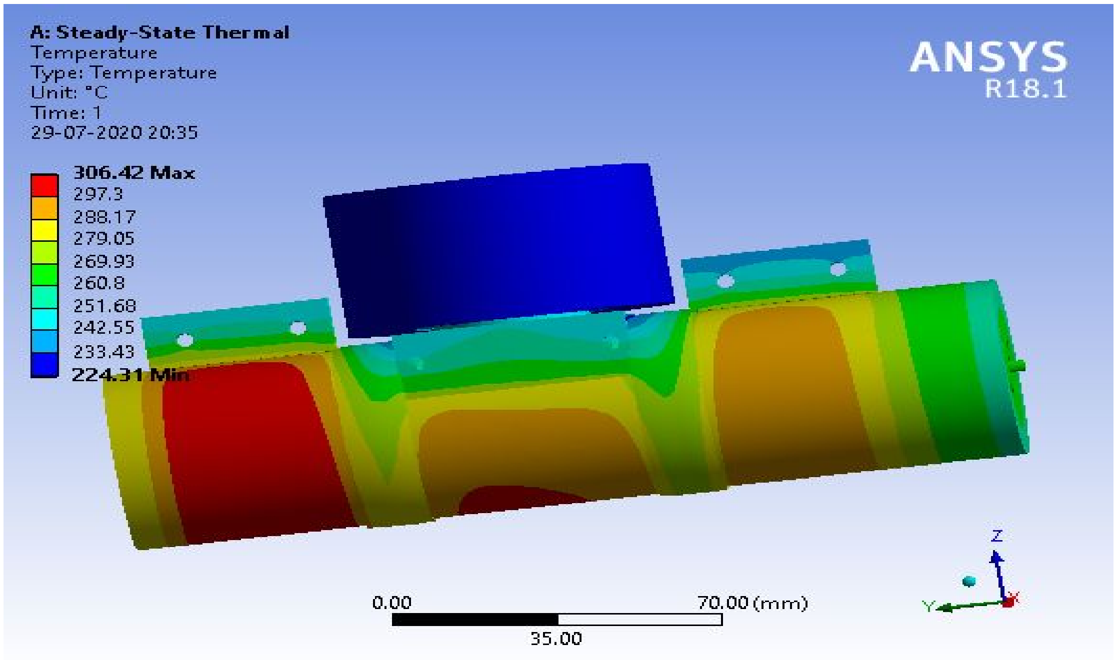

Fig 20: Complete system temperature gradient.

4.1.5. Conclusion:

1. The temperature gradient for nylon is between 270-350 degrees, therefore nylon is in liquid state but is also not fuming.
2. According to the analysis, the temperature gradient is between 270-292 degrees. This satisfies the requirement.

4.2. MATLAB-Simulink simulation of the heating module and PID controller:

For finding constants of PID controllers virtual thermal circuits are built in the matlab-simulink. Also this simulation determines time required to reach the required temperature and power requirement.

4.2.1 Thermal Circuit:

In the Simulink complete thermal circuit is built with a PID controller, for that the target temperature is kept 270^{0}C which is 543 K is given as constant in the below block diagram. Heater input varies between 0 W to 400W according to PID input.

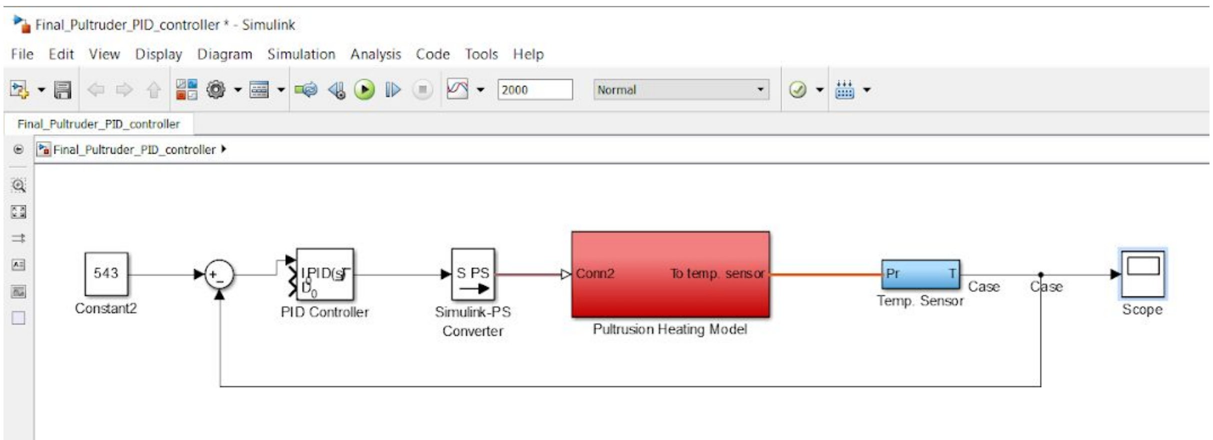

Fig 21: MATLAB feedback loop of PID controller.

As shown in the thermal circuit below two thermal masses were considered: one is mass of the iron pipe in which heating is done and 200g mass nylon in the heating module. Furthermore, conductance inside and between the pipe and nylon is considered. In the end loss to the atmosphere is considered to form an opening for the fiber insertion. The temperature of nylon mass is taken out as reading and for the PID feedback loop.

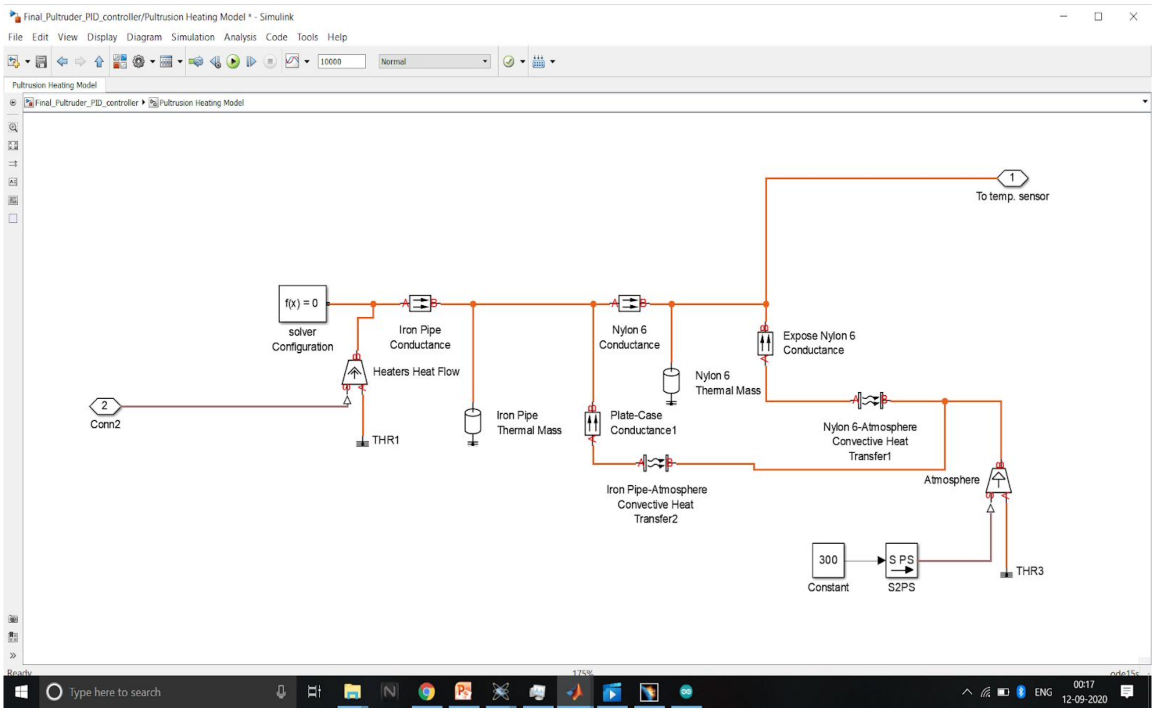

Fig 22: Thermal circuit of 'Pultrusion Heating Module.

4.2.2 PID Tuning:

If only a proportional controller is used temperature fluctuates up to $\pm 20^0$C.PID constants were tuned manually up to which fluctuation stops and the temperature is constant over time. Melting temperature reaches after 800s.

PID constants are, K_p=200,

K_i=1.2,

K_d=0.2.

4.2.3 Results:

Graph of temperature vs time is plotted as shown below.

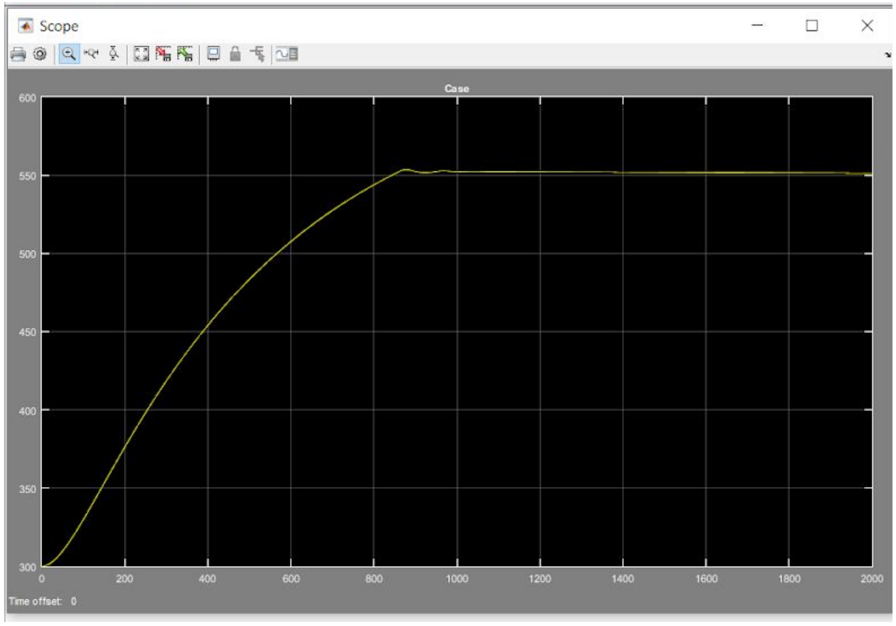

Fig 23: Simulated temperature reading of nylon inside heating module vs time(s).

4.2.4. Conclusion:

1. 400 W of heater power is required considering energy loss to the atmosphere.
2. The temperature reaches to 270^{0}C in around 800s.
3. PID constants are determined which are K_p=200, K_i=1.2, K_d=0.2.

4.3. 3D printing nozzle:

The nylon and fiber filament enters the nozzle at a temperature of 300°C which is ideal for 3D printing. Thermal analysis of the nozzle is done so as to check whether it is not losing that temperature to the environment due to losses.

4.3.1. CAD of 3D printing nozzle:

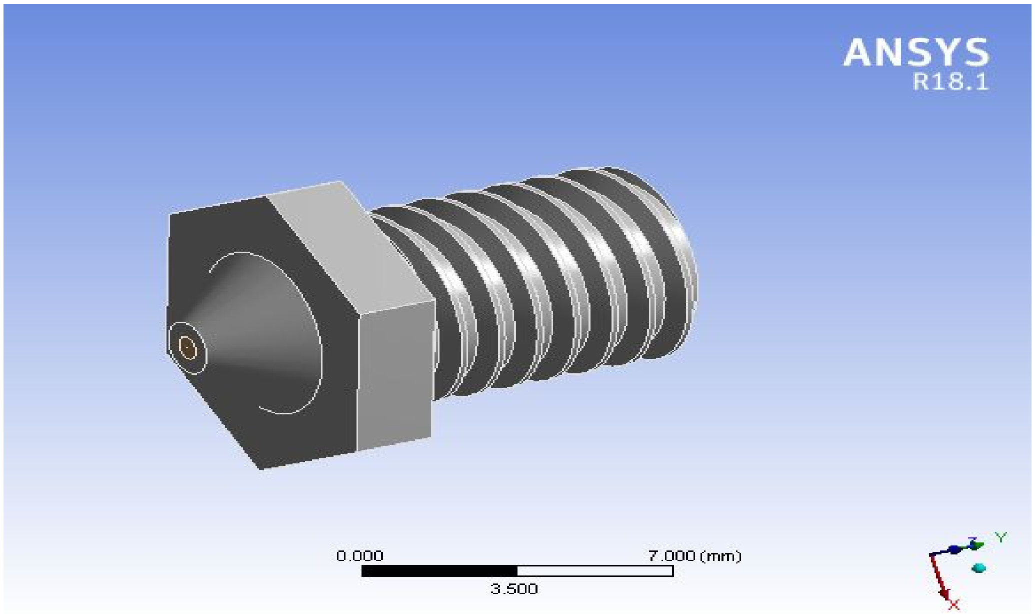

Fig 24: 3D Printing Nozzle.

The nozzle contains threads which are used to thread in the nozzle. Nozzle contains a hole through which the filament passes for 3D printing.

4.3.2. Mesh:

The mesh used was a mix of hex and tetrahedron mesh. The Mesh size used is 1mm.

Mesh quality check: quality check is done to ensure that the results obtained can be trusted.

ASPECT RATIO	1.127
SKEWNESS	0.7
No. OF ELEMENTS	5877
No. OF NODES	16982

Table 3: Mesh Specification for Nozzle

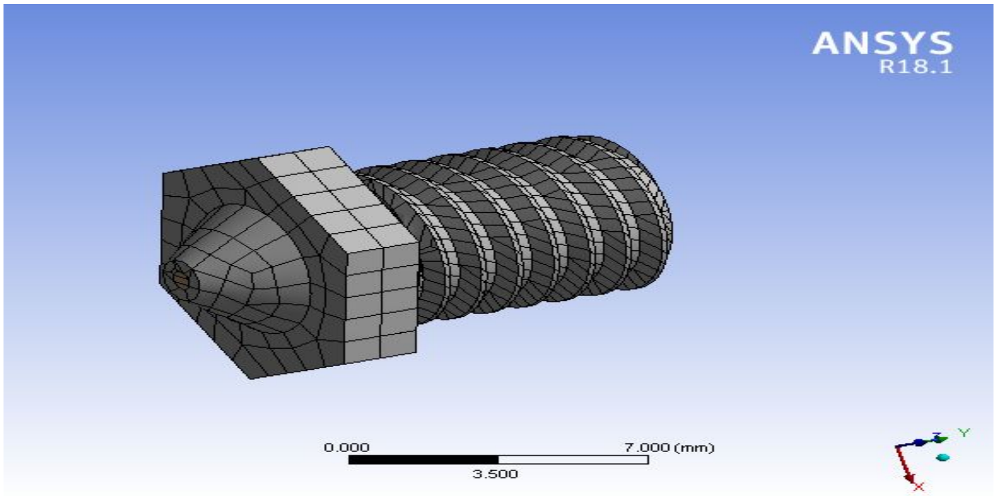

Fig 25: Mesh Illustration for Nozzle.

4.3.3. Thermal loading constraints:

The thermal constraints are:

1. The temperature of a filament of 300°C
2. There are losses due to radiation with an emissivity of 0.8.

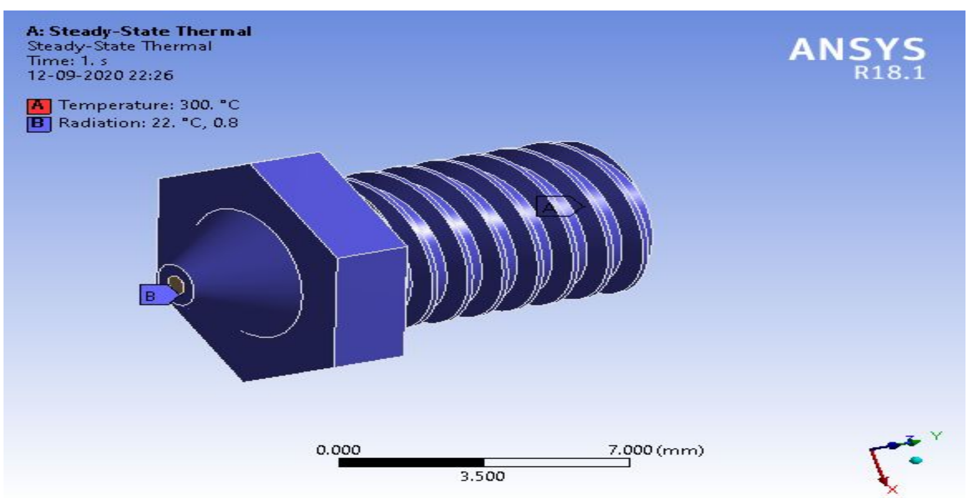

Fig 26; Thermal loading constraints for Nozzle.

4.3.4. Results:

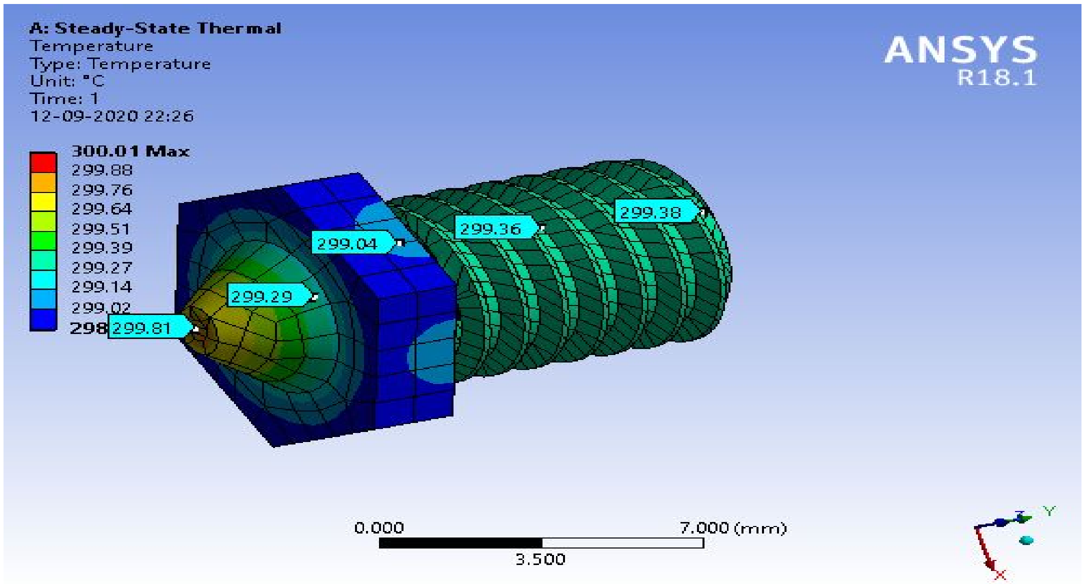

Fig 27: Thermal Results for Nozzle.

The temperature is maintained at around 300°C throughout the nozzle.

4.3.5. The conclusion from Thermal Analysis of Nozzle:

1. The filament temperature is maintained around 300°C which is ideal for 3D printing of the filament.