

# Mathematical Modelling & Pressure Drop Analysis of Fused Deposition Modelling Feed Wire

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**Abstract**— Fused deposition modelling machine is an environment friendly additive manufacturing technology which is free from geometry of part to be print. In this technology Poly lactic acid (PLA) a biodegradable feed wire is used as a raw material to print the part. In this paper a mathematical model of feed wire is developed. Here in it the expression of total pressure drop is obtained by using Taylor's series expression including the temperature effect according to Arrhenius equation. The paper deals the effect of nozzle geometrical parameters like nozzle angle, exit diameter and section height on pressure drop and melts flow behavior of 3 mm PLA feed wire. The total pressure drop analysis is done by using the mathematical expression by varying nozzle angle from 30° to 120° and exit diameter from 0.2 mm to 0.4 mm.

**Keywords**- Additive Manufacturing, Modelling Feed Wire, Nozzle Geometrical Parameters, Nozzle Pressure Drop, Taylor's Series.

## I. INTRODUCTION

Fused deposition modelling is categorized as an additive manufacturing technology which is based on the feed wire extrusion process through which part development takes place layer to layer deposition of raw material. The layer by layer deposition process repeated until the part completion takes place. The feed wire is feed by feeder mechanism in to isothermal nozzle which is maintained up to or above the glass transition temperature of the feed wire. The glass transition temperature of the feed wire is approximately 0.3  $T_m$  of (where  $T_m$  is the melting point of feed wire) PLA feed wire. The feed wire is extruded at 200-220 °C from nozzle to get continuous discharge through exit of nozzle. The best possible exit diameter and nozzle angle parameter can be decided on the basis of pressure drop analysis for which a mathematical model of feed wire is developed. The feed wire element consider initially cylindrical in shape (as shown in Fig. 1) to get the expression of pressure drop. Now the Taylor series first order expression is used to find out the pressure drop including temperature effect by Arrhenius equation used in it. Now the study of feed wire at its melt flow condition is consider viscous laminar flow with Reynolds no < 5. The study of feed wire is based on the following given assumptions.

- Study state flow.
- Flow is laminar ( $Re < 5$ ) means Inertia effect is dominate to viscous force.
- Temperature of nozzle is constant over the whole nozzle (circular cross-section and tapered section).
- Fully developed flow means velocity gradient is zero.
- Incompressible flow.
- Effect of gravity force is negligible.
- There is no external force like magnetic etc.
- Velocity near the wall surface is zero.

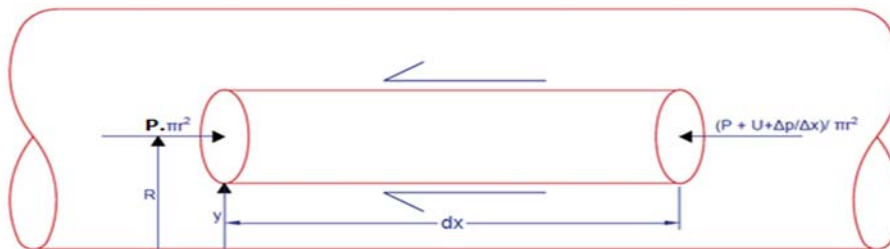


Fig. 1. Schematic diagram of viscous flow through nozzle

Fig. 1 shows the cylindrical element of feed wire which is under consideration for the study, now according to equilibrium condition the pressure in terms of pressure force and shear stress (in terms of shear force) are represented according to Taylors series first order derivatives (discussed below).

## II. MATHEMATICAL MODELLING OF FEED WIRE

The mathematical expression to find out the pressure drop for constant circular section 1 and section 2 is derived in this section and different symbols used for understanding mathematical equation are listed in TABLE 1.

TABLE 1: Nomenclature of Symbols Used

Symbol	Nomenclature
P	Pressure
R	Radius of filament
$z_1$ and $z_2$	Vertical height of nozzle section 1 and section 2
$\Theta$	Nozzle tip angle
$\phi_f$	Fluidity constant with respect to substance
M	Melt flow index
$v_i$	Input velocity
$T_w$	Working temperature
$T_{abs}$	Absolute temperature in $^0k$
$T_{ref}$	Temperature at which $\phi$ and $m$ calculated
$d_1$	Inlet diameter of nozzle
D	Filament diameter
$r_1$ and $r_2$	$r_1$ and $r_2$ are the radius of nozzle
$\mu$	Viscosity of semi liquid substance
$E_a$	Activation energy
$\Omega$	Angular velocity
$\tau_r$	Shear stress
Q	Discharge of melt wire
$u_{avg.}$	Average velocity of the fluid flow
$\Delta P_1$	Pressure drop in section 1
$\Delta P_2$	Pressure drop in section 2
$\Delta P_{total}$	Total pressure drop across the nozzle

According to Taylor's series expression:

$$p.\pi r^2 - (p + \frac{\partial p}{\partial z} dz)\pi r^2 - \tau.2\pi r dz = 0 \quad (1)$$

After solving this equation this produce

$$\tau_r = -\frac{\partial p}{\partial z} \cdot \frac{r}{2} \quad (2)$$

Now  $\tau_r$  according to Ostwald power law equation and dynamic viscosity

$$\mu = c \left( -\frac{\partial u}{\partial r} \right)^{m-1} \quad (3)$$

Where  $c$  is the flow consistency index,  $\frac{\partial u}{\partial r}$  is the shear strain rate and  $m$  is the non-dimension index.

$$\text{Let } m = \frac{1}{n}$$

$c = \phi_f^{-(1/n)}$  Then equation no (2) and (3) becomes

$$\mu = \phi_f^{-1/n} \left( -\frac{\partial u}{\partial r} \right)^{(1/n)-1} \quad (4)$$

$$\tau_r = \phi_f^{-1/n} \left( -\frac{\partial u}{\partial r} \right)^{(1/n)} \quad (5)$$

Now using equation no (2) and (5)

$$\frac{\partial u}{\partial r} = -\phi_f \left[ -\frac{\partial p}{\partial z} \frac{r}{2} \right]^n \quad (6)$$

Integrate equation no (6)

$$\int \partial u = -\phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \int r^n \partial r \quad (7)$$

$$u_r = -\phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{R^{n+1}}{n+1} + c \quad (8)$$

Boundary condition

At  $r=R$ ,  $u_R=0$

$$c = \phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{R^{n+1}}{n+1} \quad (9)$$

Now put value of c constant in equation no (8) from equation no (9)

$$u_r = \phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{1}{n+1} [R^{n+1} - r^{n+1}] \quad (10)$$

Discharge quantity

$$\int dq = \int 2\pi r \cdot dr u_r \quad (11)$$

Put value of  $u_r$  in equation no (11), which gives discharge after integration

$$Q = \pi \phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{R^{n+3}}{n+3} \quad (12)$$

Average velocity  $\bar{u} = \frac{\pi \phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{R^{n+3}}{n+3}}{\pi R^2} \quad (13)$

$$\bar{u} = \phi_f \left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n \frac{R^{n+1}}{n+3} \quad (14)$$

$$\left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right]^n = \frac{(n+3)\bar{u}}{R^{n+1}\phi_f} \quad (15)$$

$$\left[ -\frac{\partial p}{\partial z} \frac{1}{2} \right] = \left[ \frac{(n+3)\bar{u}}{R^{n+1}\phi_f} \right]^{\frac{1}{n}} \quad (16)$$

$$\int \partial p = -2 \left[ \frac{(n+3)\bar{u}}{R^{n+1}\phi_f} \right]^{\frac{1}{n}} \int \partial z \quad (17)$$

After integration the pressure drop is

$$p_2 - p_1 = 2 \left[ \frac{(n+3)\bar{u}}{R^{n+1}\phi_f} \right]^{\frac{1}{n}} (z_1 - z_2) \quad (18)$$

Now the viscosity is the function of temperature so according to Arrhenius Equations

$$H(T_w) = e^{\left[ \frac{E_A}{T_w - T_{ab}} + \frac{1}{T_{ab} - T_{rf}} \right]} \quad (19)$$

Where  $E_A$  =Activation Energy

$T_{ab}$  =Absolute temperature

$T_{rf}$  =Reference temperature at which  $H(T_w) = 1$  and  $T_{ab} = 0$

$T_w$  =Working Temperature which is slightly above the melting temperature of PLA

So the pressure difference for zone first is

$$(p_2 - p_1) = 2 \left[ \frac{(n+3)\bar{u}}{R^{n+1}\phi_f} \right]^{\frac{1}{n}} (z_1 - z_2) e^{\left[ \frac{E_A}{T_w - T_{ab}} + \frac{1}{T_{ab} - T_{rf}} \right]} \quad (20)$$

Similarly for taper section the pressure drop will be

$$(p_3 - p_2) = \frac{2n}{3 \tan\left(\frac{\theta}{2}\right)} \left[ \frac{\bar{u}}{\phi_f} \right]^{\frac{1}{n}} \left[ \frac{1}{r_3^{\frac{3}{n}}} - \frac{1}{r_2^{\frac{3}{n}}} \right] \left[ r_2^2 2^{n+3} (n+3) \right]^{\frac{1}{n}} e^{\left[ \frac{E_A}{T_w - T_{ab}} + \frac{1}{T_{ab} - T_{rf}} \right]} \quad (21)$$

The Total Pressure Drop

$$\Delta p_{total} = (p_2 - p_1) + (p_3 - p_2) \quad (22)$$

The nozzle angle can be calculate by using formula

$$\tan\left(\frac{\theta}{2}\right) = \frac{r_2 - r_3}{\Delta z_2} = \frac{d_2 - d_3}{\Delta z_2} \quad (2\Omega = 2\pi N/60, N \text{ is in rpm})$$

### III. OPERATING CONDITION OF FEED WIRE

The properties of Poly-lactic acid (PLA) feed wire are mentioned in TABLE 2 below with filament operating condition. The feed wire convert it into semi liquid form as the temperature of Poly lactic acid (PLA) feed wire reach up to the glass transition temperature. The glass transition temperature generally is 0.3  $T_m$  of melting point temperature. As the feed wire temperature raised up to this temperature the wire start to melt and it convert from solid to semiliquid state and flow in nozzle according to physical law of nature these are conservation of mass, conservation of momentum, and conservation of energy.

TABLE 2: Filament Operating Conditions

Sr. No	Property	Symbol	Values	Unit
1	Viscosity	$\mu$	0.000037	Pa-s
2	Temperature (at which phi and n' are calculated)	T	333	$^{\circ}\text{K}$
3	Working Temperature $T_w$	$T_w$	523	$^{\circ}\text{K}$
4	Absolute temperature	$T_{abs}$	300	$^{\circ}\text{K}$

TABLE 3: Representation of the Poly-lactic Acid (PLA) Physical & Thermal Properties.

Sr. No	Property	Values	Units
1	Viscosity of PLA	0.265-0.467	M Ps-s
2	Density of PLA	1.25	gm/cm <sup>3</sup> at 21.5°C
3	Thermal conductivity	0.13	W/M <sup>0</sup> k
4	Thermal diffusivity	0.056	m <sup>2</sup> /sec
5	Specific heat	1800	J/Kg <sup>0</sup> K
6	Feed rate	2.247-2.67	m/sec
7	Yield Tensile Strength	52	(MPa)
8	% Elongation at Yield	10-100	%
9	Flexural Modulus	345-450	(MPa)
10	Melting Point	120-170	(°C)
11	Glass Transition Temperature	54-56	(°C)
12	Shear Modules	2.4	GPa

TABLE 4: Boundary Conditions for Mathematical Model

Sr. No	Boundary Condition	Values	Units
1	Inlet Velocity	0.00000399	m/s
2	Inlet Temperature	300	<sup>0</sup> K
3	Temperature of surface (with circular and tapered section)	523	<sup>0</sup> K
4	Back flow temperature	300	<sup>0</sup> k
5	Gauge Pressure at inlet and outlet	0	Pa

#### IV. RESULT AND DISCUSSION

TABLE 5 & TABLE 6 represents the pressure drop analysis section wise as total pressure drop using equation no 21, 22, 23 for melt flow of feed wire across the nozzle, for various nozzle geometrical condition with same operating condition, raw material, boundary condition as mentioned in TABLE 2, TABLE 3 & TABLE 4 above respectively. TABLE 6 represents the total pressure drop for 30<sup>0</sup>, 60<sup>0</sup>, 90<sup>0</sup> and 120<sup>0</sup> nozzle angle. The total pressure drop evaluated in TABLE 5 with respect to each nozzle angle at different exit diameter shows that the pressure drop decrease as the exit diameter of the nozzle exit diameter increases from 0.2 mm to 0.4 mm. At each nozzle angle with different exit dia. 0.4 mm, 0.3 mm and 0.2 mm the numerical value of pressure drops are mentioned in below TABLE 7, TABLE 8, TABLE 9 & TABLE 10 and its graphical representation are in Fig. 2, Fig. 3, Fig. 4, Fig. 5 and Fig. 6. The results shows that as pressure drop decreases by increasing the nozzle exit diameter from 0.2 mm to 0.4 mm and nozzle angle from 30 degree to 120 degree.

TABLE 5: Total Pressure Drop for Melt Flow Wire across Nozzle for Different Nozzle Angle and Exit Diameter

Sr. No	(In Degree) $\Theta$	Di (mm)	D <sub>0</sub> (mm)	Z <sub>1</sub> (mm)	Z <sub>2</sub> (mm)	Pressure	Pressure Difference for section 2 (Pa)	Total Pressure Drop (Pa)	Total Pressure (N/mm <sup>2</sup> )
1	30	3	0.4	20.148	4.85	4.94E-10	5.40E-05	5.40E-05	53.995111
2	30	3	0.3	19.967	5.038	4.90E-10	0.0003201	0.0003201	320.05054
3	30	3	0.2	19.77	5.224	4.84E-10	0.0037366	0.0037366	3736.6336
4	60	3	0.4	22.748	2.25	8.81E-10	3.98E-05	3.98E-05	39.785437
5	60	3	0.3	22.66	2.3382	8.78E-10	0.0002335	0.0002335	233.46579
6	60	3	0.2	22.57	2.424	8.74E-10	0.0027518	0.0027518	2751.805
7	90	3	0.4	23.7	1.3	1.52E-09	3.94E-05	3.94E-05	39.378196
8	90	3	0.3	23.65	1.35	1.57E-09	0.0002311	0.0002311	231.05762
9	90	3	0.2	23.6	1.4	1.57E-09	0.002711	0.002711	2711.0452
10	120	3	0.4	24.5	0.7505	1.63E-09	2.36E-05	2.36E-05	23.625302
11	120	3	0.3	24.24	0.779	1.64E-08	0.0001391	0.0001392	139.16465
12	120	3	0.2	24.19	0.808	1.86E-08	0.0016285	0.0016285	1628.5472

TABLE 6: Pressure Drop at Different Nozzle Angle

Sr. No	Exit diameter of nozzle in mm	Nozzle angle at 30 <sup>0</sup>	Nozzle angle at 60 <sup>0</sup>	Nozzle angle at 90 <sup>0</sup>	Nozzle angle at 120 <sup>0</sup>
1	Pressure (N/mm <sup>2</sup> ) ( nozzle exit dia. 0.4 mm)	53.99511117	39.78543747	39.37819616	23.6253017
2	Pressure (N/mm <sup>2</sup> ) ( nozzle exit dia. 0.3 mm)	320.0505449	233.4657888	231.0576205	139.164653
3	Pressure (N/mm <sup>2</sup> ) (nozzle exit dia. 0.2 mm )	3736.633611	2751.805007	2711.045225	1628.547203

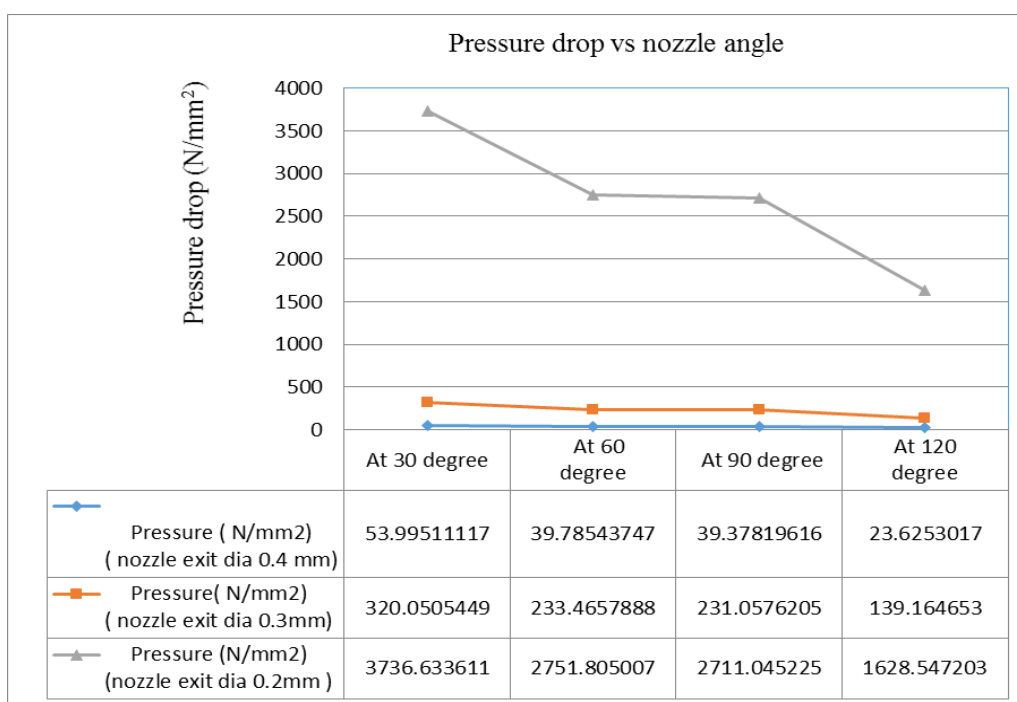


Fig. 2. Pressure drop variation over the nozzle length for exit diameter 0.2 mm, 0.3 mm and 0.4 mm

The Fig. 2 represents the variation in pressure drop over the nozzle length by varying exit diameter of nozzle. In this graph the value of pressure drop at nozzle exit diameter 0.4 mm is 53.99 N/mm<sup>2</sup> at nozzle angle 30<sup>0</sup>, 39.785 N/mm<sup>2</sup> at 60<sup>0</sup>, 39.78 N/mm<sup>2</sup> at 90<sup>0</sup> and 23.625 N/mm<sup>2</sup> at 120 degree. For 0.3 mm exit diameter the pressure drop are 320.05 N/mm<sup>2</sup> at 30<sup>0</sup>, 233.4657 N/mm<sup>2</sup> at 60<sup>0</sup> and 231.05 at 90<sup>0</sup> and 139.1646 N/mm<sup>2</sup> at 120<sup>0</sup> respectively. Similarly for 0.2 mm exit dia. pressure drops are 3736.63 N/mm<sup>2</sup> at 30<sup>0</sup>, 2751.80 N/mm<sup>2</sup> at 60 degree, 2711.04 N/mm<sup>2</sup> at 90<sup>0</sup> and 1628.54 N/mm<sup>2</sup> at 120<sup>0</sup> nozzle angle respectively. The pressure variation with respect to nozzle angle also varies in this graph, the pressure changes with the nozzle angle 30<sup>0</sup> to 120<sup>0</sup> and with each exit diameter. The value of pressure drop is maximum at 0.2 mm exit dia. with 30 degree nozzle angle and minimum at 0.4 mm dia. with 120<sup>0</sup> nozzle angle. Highest pressure drop at exit gives minimum layer thickness, less material consumption rate, fine resolution, accuracy and good strength in part but to feed the wire in to nozzle high torque is required and situation of nozzle jamming arises and repeat constantly. So to rectify nozzle jamming problem exit diameter of nozzle or nozzle angle have to increase. Here to achieve the best possible resolution, accuracy, strength and other required parameter the optimum parameter of nozzle angle is 120<sup>0</sup> with because 0.2 mm exit diameter 120<sup>0</sup> reduce feed force and 0.2 mm exit diameter gives best resolution. Graph shows the pressure variation over the nozzle length by varying nozzle angle from 30<sup>0</sup> to 120<sup>0</sup> and exit diameter from 0.4 mm to 0.2 mm.

TABLE 7: Pressure Drop at 30<sup>0</sup> for Feed Wire.

Sr. No	Pressure drop at nozzle angle 30 <sup>0</sup>	
	Exit diameter of nozzle (mm)	Pressure (N/mm <sup>2</sup> )
1	0.2	3736.6336
2	0.3	320.05054
3	0.4	53.995111

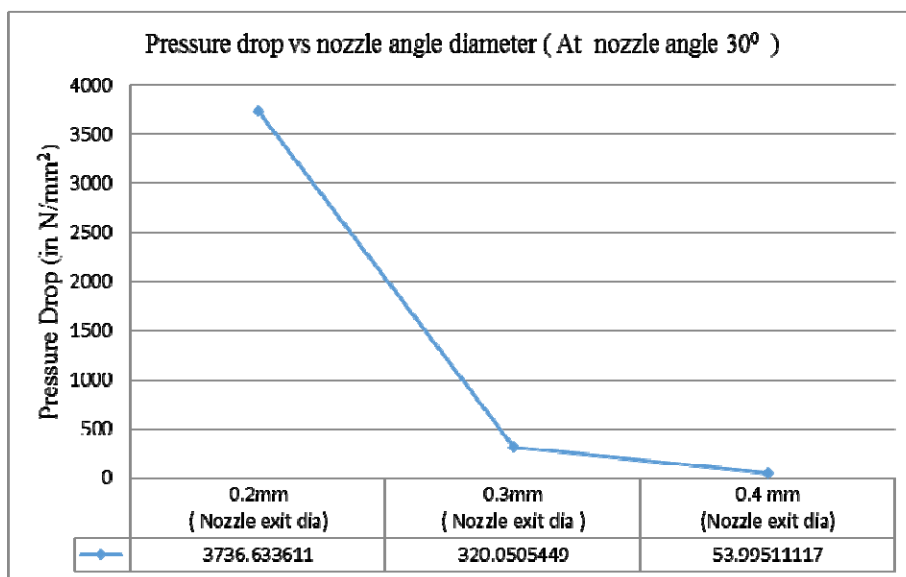


Fig. 3. Pressure drop variation over the nozzle length for nozzle angle 30°

The Fig. 3 represents the pressure drop values from inlet to outlet at constant nozzle angle of 30 degree by varying exit dia. from 0.2 mm to 0.4 mm.

TABLE 8: Pressure Drop at 60° for Feed Wire

ZZ	Pressure drop at nozzle angle 60°	
	Exit diameter of nozzle (mm)	Pressure (N/mm <sup>2</sup> )
1	0.2	2751.805
2	0.3	233.46579
3	0.4	39.785437

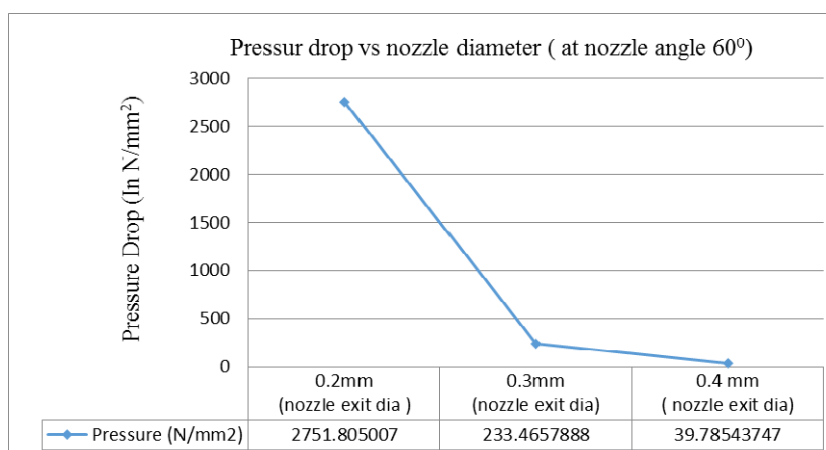


Fig. 4. Pressure drop variation over the nozzle length for nozzle angle 60°

The Fig. 4 represents the pressure drop values decreases from inlet to outlet at constant nozzle angle of 60 degree by varying exit diameter from 0.2 mm to 0.4 mm.

TABLE 9: Pressure Drop at 90° for Feed Wire

Sr. No	Pressure drop at nozzle angle 90°	
	Exit diameter of nozzle (mm)	Pressure (N/mm <sup>2</sup> )
1	0.2	1628.547203
2	0.3	139.164653
3	0.4	23.6253017

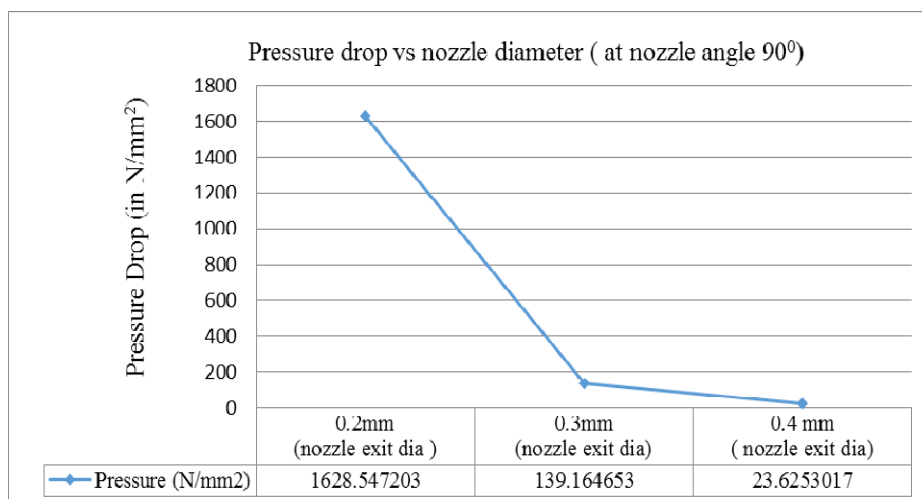


Fig. 5. Pressure drop variation over the nozzle length for nozzle angle 90°

The Fig. 5 represents the pressure drop values varies 1628.54 N/mm<sup>2</sup> to 23.65 N/mm<sup>2</sup> from inlet to outlet at nozzle angle of 90° by varying exit diameter from 0.2 mm to 0.4 mm.

TABLE 10: Pressure Drop Analysis at 120° for Feed Wire

Sr. No	Pressure drop at nozzle angle 120°	
	Exit diameter of nozzle (mm)	Pressure (N/mm <sup>2</sup> )
1	0.2	313.7335473
2	0.3	26.80669419
3	0.4	4.551065038

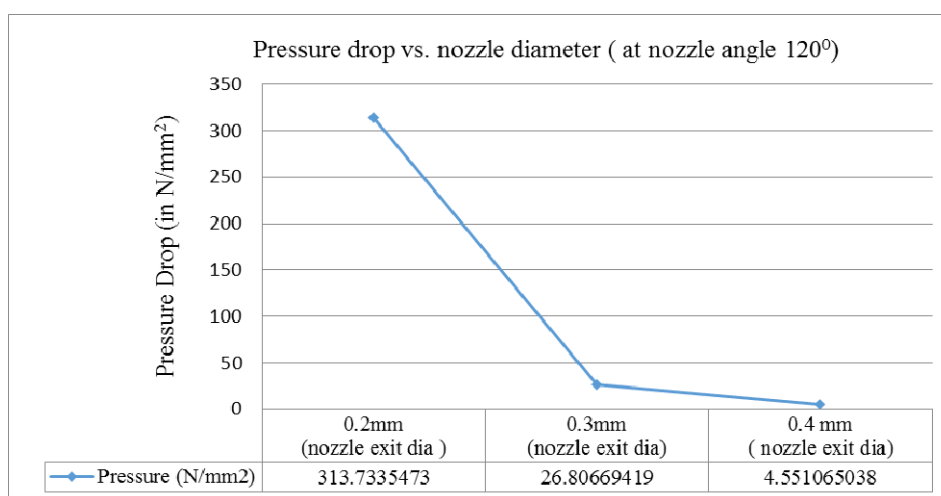


Fig. 6. Pressure drop variation over the nozzle length for nozzle angle 120°

The Fig. 6 represents the pressure drop values from 313.73 N/mm<sup>2</sup> to 4.55 N/mm<sup>2</sup> from inlet to outlet at constant nozzle angle of 120° by varying exit diameter from 0.2 mm to 0.4 mm. Pressure drop has significant role in controlling the layer thickness, resolution, material consumption, gaps between the adjacent layer and also control the feed force which is required to feed the wire in to nozzle. Here every graph shows the same trends of pressure drop by varying nozzle exit diameter as well as nozzle angle. To optimize the all above parameter the results recommend nozzle angle should be 120° with intermediate diameter 0.3 mm for to achieve the best output result.



## V. CONCLUSION

The pressure drop analysis across the nozzle is done by using mathematical modelling of poly-lactic acid (PLA) feed wire. The results of mathematical analysis shows that as the nozzle angle increases from 30°, 60°, 90° and 120° with combination of 0.2 mm, 0.3 mm, and 0.4 mm exit diameter, the pressure drop decreases with nozzle exit diameter from 0.2 mm, 0.3 mm and 0.4 mm. The best possible combination of nozzle angle and exit diameter are achieved for thin extruded wire without any irregular flow of melt flow behaviour. For 3 mm feed wire the best possible combination of exit diameter and nozzle angle is 0.2 mm with 120°. The pressure drop and quality of filament depends on nozzle geometrical parameter like nozzle angle and exit diameter. The results obtained by applying mathematical modelling can be verified by computational analysis.

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