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Research Article

Parametric analysis of Single Screw extruder for processing of re-cycled plastics

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Abstract

Plastics are endangering environment due to excess usage by the urbanized communities all round the world and due to its non-decomposable property, handling the waste is hazardous. In the present work, a plastic shredding machine with hot barrel is designed using the fundamentals of rheology, polymer science, heat transfer and design aspects of machine components for new product development. The specific flow rate, pressure drop, shear rate, residence time, conveying efficiency are calculated and presented for parametric analysis. The behavior of plastic melt flow during the melt conveying zone, heat transferred, and adiabatic temperature rise is discussed.

Keywords: *Screw conveyor, viscosity, pressure drop, LDPE, HDPE, shear rate, extruder, flow rate.*

1. Introduction

Plastics are inexpensive, light weight and durable, due to which there is a severe demand for its usage and disposing them is an issue. Re-cycling plastics and usage are causing health hazards and there are severe restrictions from statutory organizations , government policies all round the globe in usage of re-cycled plastics. Plastic recycling is the process of recovering scrap or waste plastic and reprocessing the material into useful products. Since plastic is non-biodegradable, recycling is a part of global efforts to reduce plastic in the waste stream, especially the approximately eight million metric tons of waste plastic that enter the Earth's ocean every year. This helps to reduce the high rates of plastic pollution. Recycling is one of the most important actions currently available to reduce these impacts and represents one of the most dynamic areas in the plastics industry today. Recycling provides opportunities to reduce oil usage, carbon dioxide emissions and the quantities of waste requiring disposal. In the present paper a single screw extruder is designed to process the recycled plastic powder shredded in waste plastic bottle shredder machine. The plastic powder is feed into the single screw extruder through gravity into the feed section of the screw extruder. The screw extruder is coupled to a electric motor driven unit with reduction gear box , in which the screw extruder rotates at a speed range of 80 Rpm to 110 Rpm.

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The screw extruder machine consists of Electrical motor drive, Barrel, Screw extruder, Electrical heating elements , filter plates and extruder die. The nomenclature of single screw extruder is indicated in figure1.

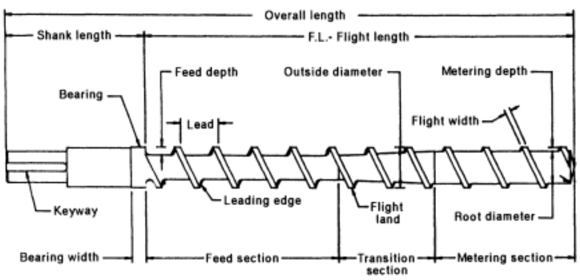


Figure 1: Nomenclature of single screw extruder.

The design of extrusion dies is based on the principles of rheology, thermodynamics, and heat transfer, which are used to calculate the viscosity of viscoelastic materials, melt plastics and heat required for melting of the plastics during transition from feed zone to extrusion zone. The parameters effecting the die design are pressure, shear rate, and residence time as functions of the flow path of the melt in the die. The pressure drop is required to predict the performance of the screw. Information on shear rates in the die is important to determine whether the melt flows within the range of permissible shear rates. Overheating of the melt can be avoided when the residence time of the melt in the die is known, which also provides an indication of the uniformity of the melt flow.

2. Design variables and parametric study

The relation between volume flow rate and pressure drop of the melt in a die can be expressed in the general form as indicated by eq.1

$$\dot{Q} = K.G^{n}\,\Delta p^{n} \qquad \text{eq.1}$$

Where $\dot{Q}$ is the volume flow rate , K is proportionality constant , Δp is the pressure drop, G is die constant and n is the power law exponent. The die constant depends on the geometry of die and for circular section is given by eq.2

$$G_{circle} = \left(\frac{\pi^{\frac{1}{n}}}{4^{\frac{1}{n}}}\right) * \left(\frac{R^{\frac{3}{n}+1}}{2L}\right) \qquad \text{eq. 2}$$

where R is radius and L is length of flow channel. As the plastic powder is flowing over the screw extruder and subjected to heating, the shear stresses are acted and shear strain rate is calculated using the relation eq.3.

$$\dot{\gamma}_{a\ circular} = \frac{4*Q}{\pi * R^{3}} \qquad \text{eq.3}$$

The adiabatic temperature rise is calculated by density, pressure drop and specific heat of the LDPE using the relation eq.4 and residence time of melt(τ) is calculated by eq.5

$$\Delta T = \frac{\Delta P}{10 * \rho_{m} * Cp_{m}} \qquad \text{eq.4}$$

$$\tau = \frac{L}{\bar{U}} \qquad \text{eq.5}$$

Melt fractures are looked like an instability of the melt flow leading to surface or volume distortions of the extrudate. Surface distortions are usually created from instabilities near the die exit, while volume distortions originate from the vortex formation at the die entrance. Melt fracture caused by these phenomena limits the production of articles manufactured by extrusion processes. The following design procedure is adopted to evaluate the melt flow properties of resin which is processed in the die.

- Step:1 • Calculate shear rate in die channel
- Step:2 • Calculate Viscosity values
- Step:3 • Calculate power law exponent
- Step:4 • Calculate Shear viscosity at Shear rate
- Step:5 • Calculate wall Shear Stress
- Step:6 • Calculate the proportionality constant
- Step:7 • Calculate Die constant
- Step:8 • Calculate pressure drop in the die channel
- Step:9 • Calculate Adiabatic Temperature rise and residence time.

Screen packs are used in polymer processing extruders to remove undesired participate matter from the melt and are placed behind the breaker plate at the end of an extrusion screw. Another important reason to implement screen packs is their assistance in better back mixing of the melt in an extruder channel, which results from the higher resistance offered by the screen to the melt flow. Better back mixing in turn improves the melt homogeneity. In addition, screen packs are also used to attain higher melt temperatures to enable better plastication of the resin. Owing to the intimate relationship between melt pressure and extruder throughput it is important to be able to predict the pressure drop in the screen packs as accurately as possible.

The volume flow rate through a small hole for a square screen opening is given by eq.6

$$\dot{q} = (400 * 6.45 * M)/(3.6 * \rho_{m} * {m_{n}}^{2} * \pi * D_{s}^{2}) \quad eq.6$$

The shear rate of the melt flow for a square opening is calculated from the eq.7

$$\dot{\gamma_{a}} = (3/0.42) * \dot{q} */(0.001 * d_{o}^{3}) \qquad \text{eq.7}$$

The screen pack assembly is indicated in figure2.

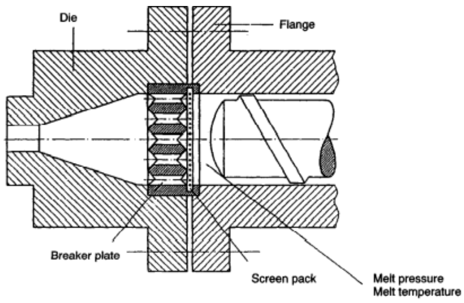


Figure 2: Screen pack in assembly

Solid conveying is the means of conveying solid particles of LDPE through the feed zone and flowing assumption were made in the process of design.

1. The polymer moves through the screw channel as a plug
2. There is no friction between the solid plastic and the screw
3. There is no pressure rise during the conveying through feed zone.

The screw extruder consists of a screw conveyor and its geometry is indicated in the figure.3

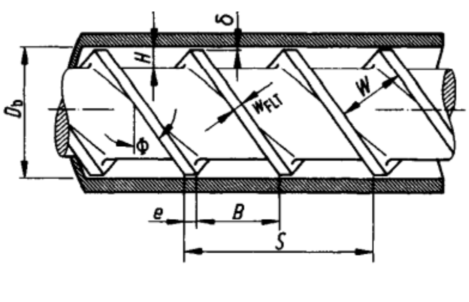


Figure 3: Screw conveyor geometry

where D_b is the barrel diameter, S is screw lead, D_s is root diameter of screw, W_{FLT} is width of flight, H is depth of feed zone , W is width of screw channel, Φ is helix angle, ψ is feed angle.

The helix angle is obtained from the principles of trigonometry and power screw concepts given by eq.8 as

$$Tan(\Phi) = S/(\pi * D_b) \quad eq.8$$

The width of the screw channel is given by eq.9

$$W = (S * Cos\Phi/v) - W_{FLT} \quad eq.9$$

Maximum Specific flow rate of the resin or the plastic is given by eq.10 expressed in cm^3/Rpm

$$(\frac{\dot{Q}}{N})_{Max} = \pi^2 * H * D_b * (D_b - H) * (W/(W + W_{FLT}) \quad eq.10$$

If f_s & f_b are the friction coefficients for the screw and barrel, then the feed angle ψ is given by the eq.11.

$$Cos(\psi) = K.Sin(\psi) + Sin(\Phi)*(K+(D_s/D_b)*cot(\Phi)) \quad eq.11$$

Where $K = (\frac{\bar{D}}{D_b}) * (sin(\Phi) + f_s Cos(\Phi))/(cos(\Phi) - f_b Sin(\Phi))$

Actual volume flow rate is given by eq.12, which is function of both feed angle and helix angle.

$$(Q/N)_{Actual} = \pi^2 * D_b * H * (D_b - H) * (Tan(\Phi) * Tan(\psi)/(Tan(\psi) + Tan(\Phi)) \quad eq.12$$

Conveying Efficiency of the single screw extruder is the ratio of specific volume flow rate actual to maximum specific volume flow rate. The conveying efficiency is given by eq.13

$$\eta = \frac{\left(\frac{\dot{Q}}{N}\right)_{Actual}}{\left(\frac{\dot{Q}}{N}\right)_{Max}} \quad eq.13$$

The resin or the plastic moves from the feed zone to melt zone and then into the metering zone. The melt zone is created by placing the heating coil on the barrel and the heat requirements are calculated from the principles of heat transfer and thermodynamics. The volume flow rate of pressure flow in m^3/sec is given by eq.14

$$\dot{Q}_p = \frac{-\pi * D_b * H^3 \left(1 - \frac{v.e}{s}\right) * sin^2\phi * cos\phi * 10^{-9}}{2*60} \quad eq.14$$

and mass flow rate during melt in Kg/hr given by eq.15 as

$$\dot{m}_p = 3600 * 1000 * \dot{Q}_p * \rho_m \quad eq.15$$

The leakage flow through the screw clearance is a function of a_d and J, which are given by eq.16 and eq.17respectively as

$$a_d = -\dot{Q}_p/\dot{Q}_d \quad eq.16$$

$$J = \delta/H \quad eq.17$$

The extruder output is finally calculated from the eq.18, and is given below

$$\dot{m} = 6 \times 10^{-5} * \pi^2 * D_b^2 * N * H * \left(1 - \frac{v.e}{s}\right) * \rho_m * sin\varphi cos\varphi * (1 - a - J)$$

The shear rate of the melt flow to determine viscosity is given by the equation eq.19

$$\dot{\gamma} = \frac{\pi D_b N}{60 H} \quad eq.19$$

The screw power consists of the power dissipated as viscous heat in the channel and flight clearance and the power required to raise the pressure of the melt. Therefore, the total power Z N for a melt filled zone is given by eq.20

$$Z_N = Z_C + Z_{FLT} + Z_{\Delta P} \quad eq.20$$

Where Z_C is the power dissipated in screw channel, Z_{FLT} is the power dissipated in Flight Clearance and $Z_{\Delta P}$ is the power required to raise the pressure of the melt.

The power dissipated in the screw channel is given by the expression eq.21

$$Z_C = \frac{v\pi^2 D_{FLT}^2 N^2 W \eta_C \Delta L (F_Z cos^2 \phi + 4 sin^2 \phi)}{36 \times 10^{14} \delta_{FLT} sin\phi} \quad eq.21$$

The power dissipated in flight clearance is given by eq.22

$$Z_{FLT} = \frac{v\pi^2 D_{FLT}^2 N^2 W_{FLT} \eta_{FLT} \Delta L}{36 \times 10^{14} \delta_{FLT} sin\phi} \quad eq.22$$

The power required to raise the pressure of the melt is given the eq.23

$$Z_{\Delta P} = 100 * \dot{Q} * \Delta P \quad eq.23$$

Heat Transfer between the melt and barrel is obtained by estimating the heat transfer coefficient. The Heat is transferred by both conductive and convective heat transfer and radiative heat transfer is sometimes neglected.

$$\bar{h} = K_m \left(\frac{N}{60 \pi a}\right)^{0.5} \left[1 - \frac{(T_f - T_m)\{1 - e^{\beta}\}}{(T_b - T_m)}\right] \quad eq.24$$

The thermal diffusivity of the melt 'a' is given by the eq.25, which will give the degree of heat penetration in solids.

$$a = \frac{K_m}{10^6 \times C_m * \rho_m} \quad eq.25$$

and β *is given by the relation eq.26*

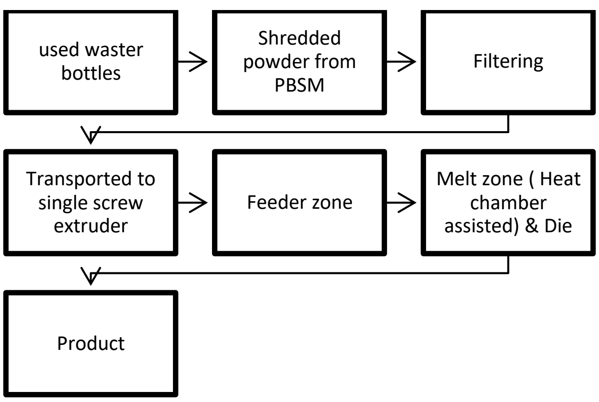
$$\beta = -\frac{10^{-6} \delta_{FLT}^2 N}{240\, a} \quad eq.26$$

The melt Temperature rise is given by the relation eq.27

$$(T_{out} - T_m) = \frac{3600\,(Z_C + Z_{FLT} + N_H)}{CP_M \dot{m}} \quad eq.27$$

3. Methods & materials

The equations eq.1 to eq.27 were incorporated in calculation f the mechanical and thermal design of plastic processing unit connected with heat chamber for extrusion of waste plastic. A plastic shredding machine was fabricated and used for shredding of waste plastic bottles. The shredded waste plastic powder is collected and transferred to the waste plastic re-cycled unit attached with auxiliary heater and extruder screw attachment with die.



The used plastic are mostly LDPE or HDPE, of which LDPE is thermoplastic made from monomer ethylene and have density of 917 ~ 930 kg/m^3, temperature of 80^{0}C , with low tensile strength and high resilience, with lower intermolecular forces. They are translucent, opaque, flexible, tough and can be recycled with a number of 4. The HDPE is also thermoplastic made from PETROLEUM (also called "alkathene" or "polythene"). The properties of HDPE is 930 ~ 970 kg/m^3 density, with melt temperature of 120^{0}C, having high tensile strength and low resilience and high intermolecular forces. They are very strong due to less branching in it's chemical composition and so interpreted to be stronger than LDPE. Disposal of such plastics are becoming a challenge and as they are not bio-degradable. Even HDPE is recycled with a number of 2. The exploded view of the PBSM is indicated in the figure 4. The obtained shredded powder is transferred to single screw extruder machine attached with auxiliary passive and electrical heating system.for melting of plastic.

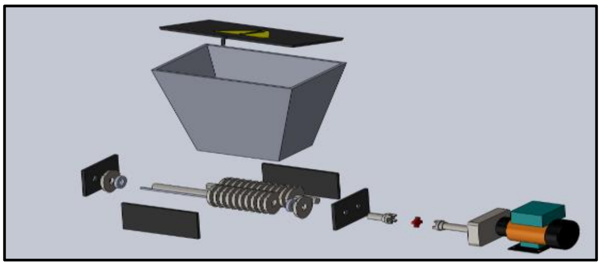


Figure 4: Exploded view of plastic bottle shredding machine

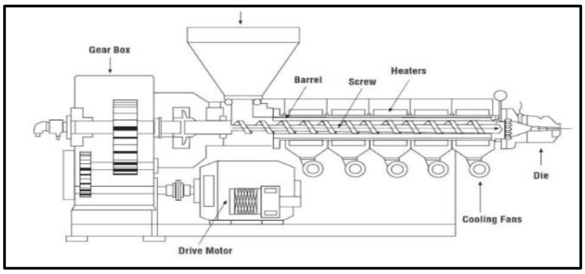


Figure 5: Single screw extruded machine

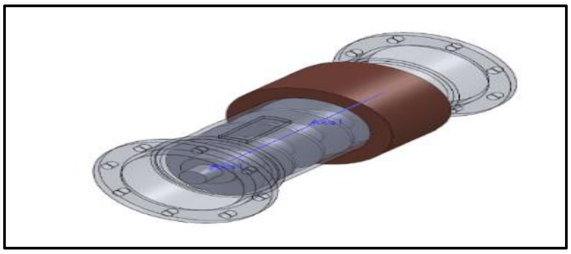


Figure 6: CAD Model of single screw extruder

4. Simulation results, data model prediction and discussion

The pressure drop across the length of extruder is dependent on radius of the extruder and length of the section. In fig.7 the effect of pressure drop in pascals is estimated and it is observed that with increasing length and increasing the radius of extruder section (circular section), the pressure drop is decreased. With increase in mass flow rate of the polymer powder the pressure drop is observed to be more at lower melting temperature than the higher melting temperature. This is graphically indicated in the fig.8.

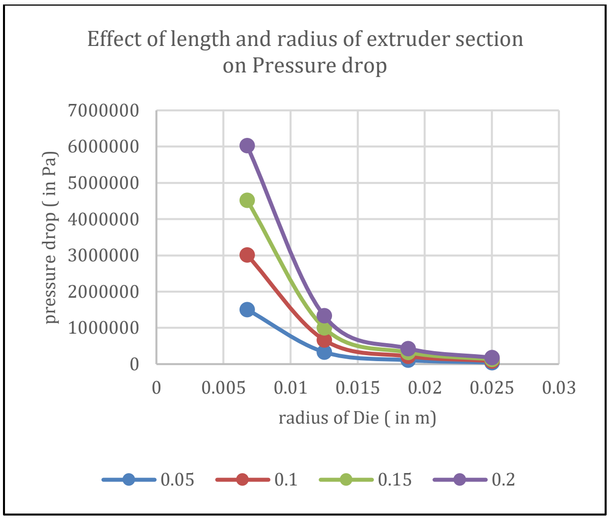


Figure 7: Effect of length & radius of extruder on pressure drop.

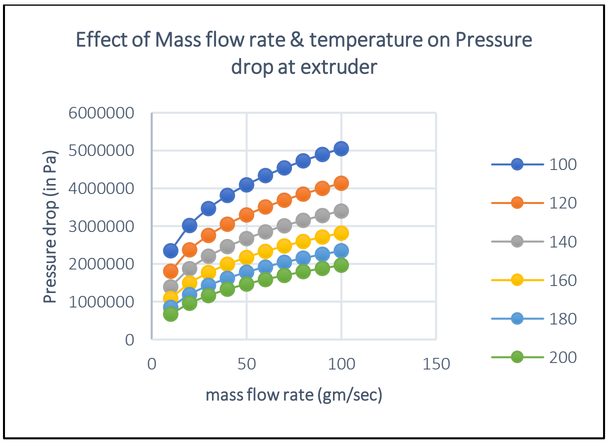


Figure 7: Effect of mass flow rate and temperature (in degrees centigrade) on pressure drop of extruder

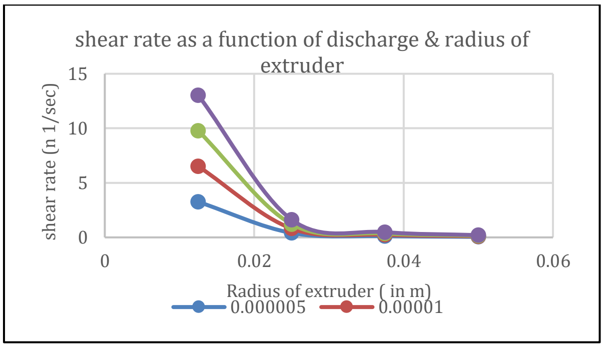


Figure 8: Shear rate as a function of discharge and radius of extruder

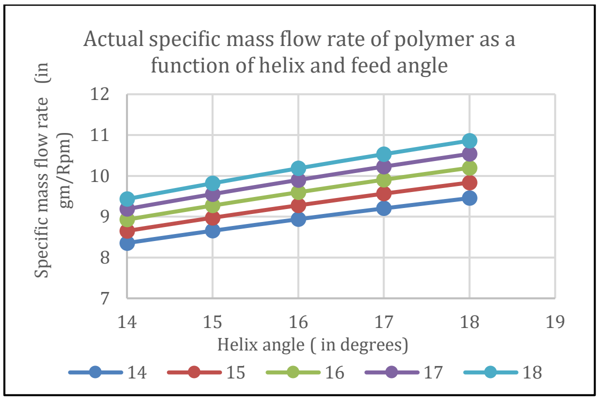


Figure 9: Adiabatic temperature rise as a function of pressure drop & density of polymer

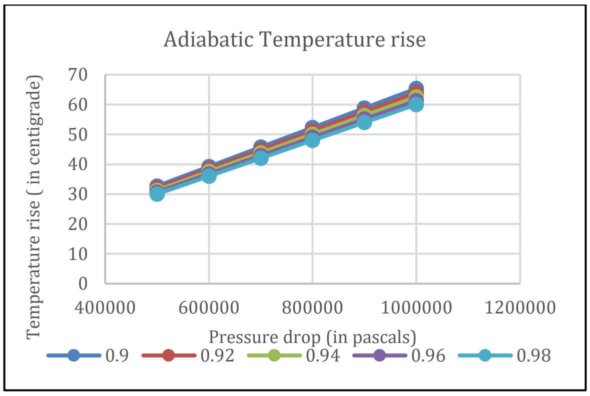


Figure 10: Specific mass flow rate as a function of barrel diameter and helix angle.

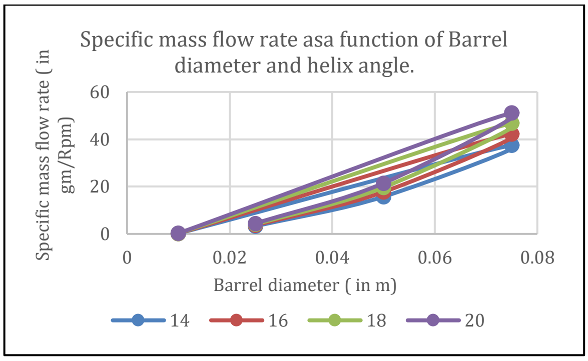


Figure 11: Actual specific mass flow rate as a function of Helix angle and feed angle.

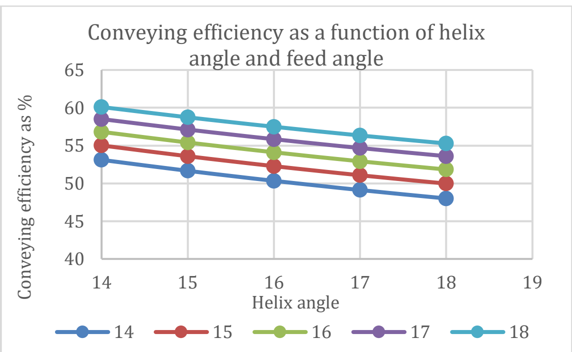


Figure 12: Conveying efficiency as a function of helix angle and feed angle.

The calculations for polymer extrusion are presented in the given table.

Table 1: Calculation of pressure drop

Physical parameter	Value	Unit
mass flow rate	10	g/sec
Density	0.917	g/cc
Discharge(Q)	1.091E-05	m3/sec
Length	0.1	mm
temperature	200	c
Radius of Extruder	0.0125	
Shear rate	7.1126423	1/s
shift factor (aT)	0.374	
Power law coeff (n)	1.7661003	
	8.5282019	
viscosity	5055.3478	pa-sec
Shear stress	35956.881	Pa
Factor of Proportionality (K)	6.398E-08	
Die Factor for circular section (G)	3.189E-05	
Pressure drop	575310.09	pa

Table 2: Calculation of conveying efficiency

Physical parameter	Value	units
Delta_T	3.69E+01	^{0}C
CP	1700	J/KgK
Time	0.5	sec
Ave_velocity	0.2	m/sec
Barrel_dia	0.05	m
Lead	0.05	m
Number of flights	1.00E+00	
root_dia	0.039	m
flight width	0.005	m
depth of feed zone	0.0075	m
Helix angle	17.65678715	degrees
width of screw channel	0.042644526	M
Maximum specific flow rate	40.6917E-05	cc/rpm
Bulk density	0.475	g/cc
specific mass flow rate	19.32858083	g/rpm
feed angle (degrees)	15	degrees
Actual volume flow rate	2.04825E-05	20.48251
actual mass flow rate	9.729193299	g/rpm
Conveying efficiency	50.33578712	%

Conclusions

A single screw extruder is analysed for operating speed of 80 Rpm having density of 0.917 gm/cc with a melt temperature of 120^{o}C. The conveying efficiency of 50.35

% is obtained with a helix angle of 17.65^0 and feed angle of 15^0. The shear rate variation, specific mass flowrate , adiabatic temperature rise and conveying efficiency are estimated and presented. The free pressure at the end of the extruder section will provide maximum mass flow rate and zero discharge at the end of the extruder section will provide the maximum pressure developed with in the extruder section. The future scope of work is based on estimation of pressure and temperature profiles in the extruder section at various locations from the feed zone using ANSYS Polyflow software for various operating pressures and various melting temperatures of the polymer powder obtained from the shredding of waste plastic bottle.

References

[1]. Shiri, Noel Deepak, et al. "Processing of waste plastics into building materials using a plastic extruder and compression testing of plastic bricks." *Journal of Mechanical Engineering and Automation* 5.3B (2015): 39-42.

[2]. Rivera, Michael L., and Scott E. Hudson. "Desktop Electrospinning: A Single Extruder 3D Printer for Producing Rigid Plastic and Electrospun Textiles." *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 2019.

[3]. Wilczyński, Krzysztof, et al. "Computer Modeling for Single-Screw Extrusion of Wood–Plastic Composites." Polymers 10.3 (2018): 295.

[4]. Martelli, Fabrizio G. *Twin screw extruders: A basic understanding*. New York: Van Nostrand Reinhold Company, 1983.

[5]. Crawford, Russell J., and Peter Martin. *Plastics engineering*. Butterworth-Heinemann, 2020.

[6]. Orisaleye, J. I., et al. "Parametric analysis and design of a screw extruder for slightly non-Newtonian (pseudoplastic) materials." *Engineering science and technology, an international journal* 21.2 (2018): 229-237.

[7]. Gopalakrishna, S., Y. Jaluria, and M. V. Karwe. "Heat and mass transfer in a single screw extruder for non-Newtonian materials." International journal of heat and mass transfer 35.1 (1992): 221-237.

[8]. Rao, N. S. and O'Brien, K.: Design Data for Plastics Engineers, Hanser Publishers, Munich (1998)