Design of an extrusion machine for the manufacture of plastic tubes

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Abstract. Currently in Colombia in the northern region of Santander, exist a large number of farmers who grow different agricultural products and require more appropriate irrigation systems hoses, but due to the high demand, local manufacturers do not meet the requirements and in many cases the hoses are brought from other parts of the country bringing higher costs. In the present work, the design of a prototype plastic extrusion machine for hose producers in the province of Ocaña was carried out. The development of the research was carried out through the execution of mathematical calculations with the support of specialized bibliographic material and a Finite Element Analysis with help of SolidWorks Simulation Software, where the geometric model of the machine in order to identify the elements subjected to maximum of efforts. The results obtained show that the prototype will be in charge of producing $\frac{1}{2}$, $\frac{3}{4}$ and 1 inch. In conclusion the prototype works in adequate conditions always ensuring high levels of safety and operation; Moreover, the machine will be low cost to promote growth and competitive capacity of hose producers, as a solution to the problems based on competitiveness, working conditions and resources economic.

1. Introduction
The north Santander region is composed of the following municipalities: Abrego, Convencion, El Carmen, El Tarra, El Zulia, Hacari, San Calixto, Sardinata, Teorama and Tibú, which represent a total of 9,058 crops as reported by an investigation carried out at the National University of Colombia [1]. On the other hand, the agroindustrial sector has been increasing production in tons in recent years but its commercial value has decreased in the different countries where the products are exported [2]; In addition, it is very important to carry out investigations with which an adequate solution can be given to machinery that has lagged behind over time.

In 1797 Joseph Bramah registered the first extrusion process to manufacture lead pipes; which consisted of the preheating of the metal which later passed through a die with a plunger by hand. Then in 1894 Alexander Dick carried out the process of extrusion to copper and bronze alloys [3].

Years later Archimedes devised a screw to remove or pump water contained in a boat. This design was applied in several industries and was used to pump a plastic mixture through a die and this was protected by a cylinder; Years later in the 19th century, the same system was covered with a jacket to
allow the circulation and transfer of heat through oil or steam (for rubber extruders). In other investigations, a few designs had some type of adaptations to obtain and/or control uniform temperatures independent those of the head and the die, where elements such as insulators of electrical conductors were later incorporated into the extruders [4].

Thermoplastics are polymeric materials that are easy to soften when heated and re-harden upon cooling (they are recycled). In general, they are soft and flexible, being widely used in processes such as extrusion and injection. The extrusion of polymers is one of the most important processes in the plastics processing industry. Likewise, several researches report that about 60% of the total polymers transformed in Colombia have gone through some extrusion process.

Nowadays the extruder consists essentially of a horizontal cylinder in which a modified Archimedean screw is rotating. This means that it is provided with a hole at the bottom of the cylinder to allow the feeding of a compound inside it to the opposite end is the head and the die. An extruder machine is mainly composed of the screw or spindle, which rotates inside a cylinder called barrel and is able to melt the material, generating a pressure at a given speed, under certain operating restrictions. If the screw is not able to generate enough pressure imposed by restrictions on flow, or if on the contrary it generates a much higher pressure than required, quality problems may occur, reflected in waste and productivity reductions [5].

In Colombia the development of prototypes of extruder machines has taken certain steps, in several universities of the national order, where work is registered such as the design of a plastic extruder more specifically the "polypropylene" developed in the Technological University of Pereira in the year 2007 [6].

2. Materials and method

For the development of this project an investigation of projective depth was carried out, given that it consists of providing a possible solution to the problems posed in a community and being able to answer questions about possible future events, in this type of research the investigations are located for inventions, programs and designs; so it is responsible for establishing how things should be, to achieve its purpose and proper functioning. Taking into account the above, the machine consists of the following elements:

2.1. Hopper

Taking into account the specifications, parameters and calculation of components, the hopper will have a diameter in the upper part of 22.54 cm and a lower diameter of 2.54 cm and a total height of 29.68 cm, with which the volume of the hopper will be calculated [7-8].

2.2. Capacity

For determine the capacity of the hopper, the weight of each PET flake must be determined. For this we determine an average volume of the leaflets and in this way find a value close to the weight that a leaflet can have. Also, we will assume that a polyethylene flake will measure 1 cm long by 1 cm wide by 0.5 mm thick, with which a capacity of 10 kg was obtained but it is recommended by safety factor only 6 kg based on 60% of its Total capacity to not generate saturation and binding.

2.3. Breaker plate

According to catalog design conditions, the exposed area consisting of an area 0.36 in$^2$=227.6 mm$^2$ was selected, calculating the number of perforations in the breaker plate according to the internal diameter of the extruder cylinder [9]. Since the internal diameter of the extrusion cylinder is 25.1 mm = 1 in; it was defined that the number of perforations is equal to 37, and having this value it is possible to calculate the diameter of the perforations that by design recommendations should be close to 3 mm.
2.4. Nozzle

It is the piece of the head that gives the final shape to the product of the extruder, because it is for the manufacture of hoses. The following Figure 1 shows the contraction percentage, taking into account that it is a hose nozzle of 20 mm [8]. Know that the diameter of the internal cylinder of the torpedo will be 33 mm. It will be coupled with a clearance of 0.1, it will be determined for this case. The lowest point of the centerpiece of the nozzle. Based on this value, we proceeded to calculate the internal diameter of the nozzle with the following Equation (1):

\[ D_{\text{Nozzle}} = D_{\text{Hose}} - \text{Contraction PET} \times D_{\text{Hose}} \]

\[ D_{\text{Nozzle}} = 14 \text{mm} - (0.0225 \times (14 \text{ mm})) \]

\[ D_{\text{Nozzle}} = 13.685 \text{ mm} \]

Knowing that the diameter of the external cylinder will be 36mm that is coupled with point 2 and therefore have the same diameter as point 3 (See Figure 1). The larger diameter (DM) of the central part of the nozzle was subsequently calculated for this case, knowing that the outer diameter of the hose is 20 mm, taking into account the following Equation (2):

\[ DM = D_{\text{Hose}} + \text{Contraction PET for the outside radius} \times D_{\text{Hose}} \]

\[ DM = 20\text{mm} + (0.0225 \times 20 \text{ mm}) = 20.45 \text{ mm} \]

Taking into account the previous Figure 1, in addition to Equation (1) and Equation (2), the values can be estimated to establish other types of diameters of plastic tubes.

2.5. Spindle

Most extruders are manufactured with the rotating spindle and fixed cylinder to increase efficiency, but for greater ease we can assume that the cylinder is the one that turns, and the spindle is the one that remains motionless [10]. Also, taking into account the material to be transformed, the shape and purpose of the products to be manufactured, a spindle for a single channel will be built. On the other hand, a value of 600 mm with a ratio of 24:1 was taken as a measure for the length of the extruder, with which we determined the diameter of the spindle: \( D = \frac{L}{r} = \frac{600}{24} = 25 \text{ mm} \).

Because it is a simple spindle of a single channel, the pitch has the same diameter value; \( t=25\text{mm} \). Knowing the value of the diameter we can determine the width of the fillet, through the following expression (Equation (3)):

\[ e = 0.12D = (0.12)(25\text{mm}) = 3 \text{ mm} \]

The geometrical configuration of the spindle depends fundamentally on the material to be transformed, for our case it is polyethylene; generally, the spindle is composed of three exactly defined zones whose lengths correspond to the value with the following expressions (Equation (4), Equation (5) and Equation (6)):

\[ L - \text{Zone Feeding} = \frac{L}{2} = \frac{600}{2} = 300 \text{ mm} \]
\[ L_{\text{Zone Compression}} = \frac{L}{4} = \frac{600}{4} = 150 \text{ mm} \]  
(5)

\[ L_{\text{Zone Dosage}} = \frac{L}{4} = \frac{600}{4} = 150 \text{ mm} \]  
(6)

In addition, with these calculations we can see that the maximum power in revolutions per minute that is required in the spindle is 185 rpm, obtaining a horsepower between 2.74 Hp and 3 Hp.

\[ \text{Figure 2. Extrusion spindle zones [10].} \]

The number of fillets is calculated by means of the ratio of diametric length that includes the diameter of the spindle and the number of fillets (see Figure 2), for plastic extruders this is determined by the following Equation (7):

\[ \frac{L}{D} = \text{Relation Length/Diameter} \]  
(7)

Solving Equation (7), we obtain the number of fillets in the spindle: \( D = 600/25 = 24 \) fillets. Based on the above, we proceeded to perform the calculation of the effective viscosity which was calculated as a function of the shear rate by means of diagrams prepared for the different materials, depending on the temperature, because the viscosities of the thermoplastics depend on this factor and the molecular weight, which decreases when heating the material and decreasing its molecular weight.

The shear velocity rate used for polyethylene in relation to the rpm parameters that were used from 52 rpm to 185 rpm, is an average of \( 131.94 \text{ s}^{-1} \) and it approaches a value from the catalog of \( 265 \text{ s}^{-1} \) [9]. In addition, the data corresponding to a cutting speed of \( (100 \text{ s}^{-1}) \) and effective viscosity at an approximate working temperature of \( 80^\circ \text{C} \) to \( 235^\circ \text{C} \) were taken. With this, an effective viscosity value of \( 750 \text{ Pa-s} \) is obtained, for the calculation effect [10].

For the production expressed as volumetric flow (Q), it is the result of three different types of flow; which are: The drag flow (\( \alpha \)), is the component caused by the rotation of the spindle. The pressure flow (\( \beta \)) is the component that opposes the flow in the system and the filtration flow (\( \gamma \)), which reduces the production due to material losses between the spindle-cylinder clearances. Therefore, the production in the dosing zone is equivalent to the total production of the spindle. The previous flows were calculated by design theories of which the following results were obtained: \( \alpha = 2.3535 \text{ cm}^3 \), \( \beta = 2.2715 \times 10^{-5} \text{ cm}^3 \) and \( \gamma = 1.07048 \times 10^{-7} \text{cm}^3 \).

2.6. Material

When selecting the material from which the spindle will be manufactured, different conditions must be taken into account, such as the chemical and mechanical factors that may affect the piece, which is sometimes subjected to aggressive conditions, corrosive elements and high stresses.

AISI 4140 commercial, which offers a series of advantages taking into account the specifications, parameters and calculations of the components that have been previously in the account. Due to its chemical composition of chromium and molybdenum, it has a fairly high hardness, high resistance to corrosion and, in addition, it has a high machinability even after being a physical treatment. In addition, the temperatures of more than 540 °C are not lost nor the mechanical characteristics even after having been subjected to an excessive work rate and high temperatures. Taking into account also its characteristics, advantages and its usual use in the manufacture of drills, cutters, spindles, couplings, rotary tables, gaskets, wheels, valves, spindles for high temperature, gear wheels, pistons,
chain links; It is an ideal material for the extrusion spindle. On the other hand, the machinability of this steel is approximately 65% compared to 100% AISI 1213 steel [11].

2.7. Engine
The necessary conditions to select the motor are:

2.7.1. Power. The power that will be used to select the motor will be that which is greater than \( N = 2.74 \text{ Hp} = 2044.04 \text{ kW} \) taking into account the voltage, current and power factor were used in the following expression: \( P = \sqrt{3}*V*I*\cos\phi \) to calculate the necessary power at which it must be produced at the speed of highest production and is the expression used for the production hoses of smaller diameters, which can be produced at a higher speed due to the speed of cooling.

2.7.2. Velocity. Since the mechanical gearbox has a maximum reduction of 6.74:1 and the minimum speed you want to reach is 52 rpm, then the engine speed will be equal to 350 rpm, and this will be the speed required for the gear reducer or at the entrance to the gearbox, depending on which option is selected, whether the reducer motor or the alternate mechanical reduction system is chosen for a three-phase electric motor if reduction respectively.

2.7.3. Electrical power supply. Given that you want a low energy consumption, the ideal would be for the engine to work at a high voltage so that energy consumption is lower, and the population to which this research is directed are people who commonly have electrical circuits in their facilities. 220 V, for which the ideal voltage is 220 V three-phase. Taking into account the above, a chain transmission system with the following characteristics was selected: Designation 1N°40-196 (1 row, number 40, and length 196”), Lubrication type B, by bath [13].

Finally, in the following Figure 3 the geometry of the extruder machine based on the geometric conditions carried out in the SolidWorks software is presented.

![Figure 3. Render of the plastic extruder machine.](image)

3. Results and discussions
Based on the calculations and considerations of the design of the machine, we proceeded to perform the finite element analysis (FEA) with the help of SolidWorks Simulation Software, taking into account ideal static conditions on the spindle subjected to the load of the mass between the cylinder which was also analyzed; as for the thermal considerations this was subjected to the heat that is transferred from the molten polymer to the spindle. The following Table 1 shows the characteristics of the material that are important when determining the considerations in the simulation:
To carry out the analysis in the finite element software, a standard solid mesh with 4 sheltered points was used. The thermal loads to which the spindle is subjected to an initial temperature of 21 °C with a surface temperature of 180 °C, obtain a heat power of P=1590 W. For the given experimental conditions, the thermal behavior on the screw in a time of 60 seconds, it can be observed in Figure 4(a) and Figure 4(b), in addition it is obtained that the maximum temperature is 220 °C in the node 1961 at the end of the spindle. Besides, the forecast is fulfilled because the maximum temperature recorded is in the expected area and with a value close to that expected, since that temperature is close to 180 ºC, which is where the polyethylene melts, in addition to the area what is presented is the indicated area, so the temperature must have a hump behavior along the screw in the extruder. As for the static charges to which the spindle is subjected, the following results were obtained:

![Simulation results for the spindle](image)

**Figure 4.** Simulation results for the spindle (a) Temperature and (b) Static loads.

From the previous Figure 4, it can be seen that the resulting maximum displacement for the spindle is 0.743973 mm present in the node 52 at the end of the spindle. Also, the simulation is adjusted to the expected because the deformation does not even reach the millimeter, so with the help of the bearings and the rotation of the spindle, it will be reduced and adjusted to the gap between the spindle and cylinder of extrusion and makes the design optimal. In addition, the fluid between the two elements will act as a barrier between both components.

For the extrusion cylinder was subjected only to the pressure exerted from the cylinder due to the increase in temperature and compression of the fluid, in order to check the correct selection of the cylinder thickness. Regarding the thermal behavior, the cylinder was subjected to the heat that is transferred to it from the resistances and for validate the behavior of heat transfer to the environment, taking into account the characteristics of the cylinder material as shown in the next Table 2:

| Name                      | Extrusion spindle |
|---------------------------|-------------------|
| Type of model             | Isotropic linear elastic |
| Material                  | Steel AISI 4140   |
| Weight                    | 1.87 kg           |
| Elastic limit             | 4.7e+008 N/m²     |
| Traction limit            | 7.45e+008 N/m²    |
| Elastic module            | 2.05e+011 N/m²    |
| Poisson’s coefficient     | 0.285             |
| Density                   | 7850 kg/m³        |
| Shear module              | 8e+010 N/m²       |
| Thermic dilatation coefficient | 1.23e-005 K⁻¹    |
Table 2. Material characteristics of the extrusion cylinder.

| Name                        | Extrusion spindle                  |
|-----------------------------|------------------------------------|
| Type of model:              | Isotropic linear elastic           |
| Material:                   | Steel AISI 4140                    |
| Weight:                     | 2.5 kg                             |
| Elastic limit:              | 3.51571e+008 N/m²                  |
| Traction limit:             | 4.20507e+008 N/m²                  |
| Elastic module:             | 2e+011 N/m²                        |
| Poisson’s coefficient:      | 0.29                               |
| Density:                    | 7900 kg/m³                        |
| Shear module:               | 7.7e+010 N/m²                      |
| Thermic dilatation coefficient: | 1.5e-005 K⁻¹                   |

For perform the analysis in the finite element software for the extrusion cylinder, a standard solid mesh with 4 sheltered points was used. The thermal loads to which the spindle was subjected to an initial temperature of 21 °C with a surface temperature of 180 °C, obtain the maximum heat power which is equal to $P=565.54$ W. The convection coefficient for the extrusion cylinder is equal to 20 W/m²K and constant with a temperature of 21 °C.

For the given experimental conditions, the simulation of the thermal behavior of the screw in a time of 60 seconds can be observed in Figure 5(a) and Figure 5(b). We can see, the extrusion cylinder has the same behavior of the spindle and is also adjusted to the characteristic bell-shaped behavior of these thermoforming machine, and also the temperature is close to the heating temperature of the polymer, it is a slightly less because of the air circulating around the cylinder [14]. Regarding the static charges to which the spindle is subjected, the following results were obtained:

![Figure 5. Simulation results for the cylinder (a) Temperature and (b) Static loads.](image)

From the previous Figure 5(a) and Figure 5(b), it is reaffirmed that the point where the cylinder supports the greatest is highlighted the same time it is in the upper part of the others, and the deformation that is presented is barely measurable around 1/10 of a millimeter which makes a conclusion that the material and the thickness selected for the extrusion cylinder was the right and perfect [13-16].

4. Conclusions
By means of the simulations carried out on the most critical elements of the design, it was determined that the materials and geometry selected surety a correct operation of the machine, since the expected and optimal temperature and displacement behaviors were obtained for the design of the same.

The design of the present machine covers what concerns the production of hoses of $\frac{1}{2}''$, $\frac{3}{4}''$ and 1'', so if you want to extrude other types of products you must make the appropriate adjustments to the design, because the production and the performance of the machine can affect the performance, in addition to which the respective extrusion nozzles should be designed.
The hopper must not exceed the stipulated capacity of 60% to avoid jamming problems in the feeding system and thus cause greater damage to the other systems of the machine, and produce higher costs, since the cylinder-screw system is very delicate and expensive.

On the other hand, it is recommended to contemplate the possibility of adding a pressure gauge in the extrusion head and thus control the pressure, because we can determine the right time to change the filters of the head, taking into account that a fall or an increase of it would indicate an excessive deterioration of the head filter; the above, to bring a better control of the production of the extruder machine.

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