

ON THE DESIGN AND TECHNOLOGY OF CO-ROTATING TWIN SCREW EXTRUDERS

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Abstract: *This document presents a systematic design approach for co-rotating twin screw extruder components, elaborated from concepts on Twin Screw Extrusion (TSE) technology and from the experience acquired by the authors in designing a mini twin screw extruder for future application as an interchangeable printing head in Additive Manufacturing (AM). Twin screw extrusion is commonly used in polymer compounding due to its good mixing performance, self-cleaning property and process flexibility. Few works have been produced in Brazil on the design of twin screw extruders, especially dealing with the screw geometry, whose elements are responsible for providing the different flows that favour material mixing and conveying inside the extruder. In addition to the complex geometry, the flexibility provided by modular elements that configure the screws makes it difficult to establish design guidelines on the subject, preventing also the development of a comprehensive software capable to inform the best screw configuration to a certain process. However, undertaking rigorously the procedure proposed to determine the geometry of the screw elements makes it possible to ensure the desired self-wiping property along with constant clearance in the intermeshing region between the screws as well as to determine some operational parameters that provide relevant information about the process. As recommended by the procedure, a mock-up of the resulting geometry was generated in order to verify the functionalities of the embodiment design. Results show that the screws can rotate without interference and the material is conveyed as expected towards the die.*

Keywords: *polymer processing, twin screw extruder design, additive manufacturing.*

1. INTRODUCTION

The growth and consolidation of new technologies starting with the Third Industrial Revolution and characterized by the intensive use of electronic and electromechanical components defines a new socio-industrial scenario. One of such transforming movements is the concept of Industry 4.0, with focus on *in loco* monitoring of productive systems. According to Jerez-Mesa et al. (2016), Additive Manufacturing (AM) is one of the main pillars of innovation in fabrication technologies. In the 2000s, the expiration of the first AM patents enabled spreading additive technologies and marketing low-end 3D printing equipment, allowing it to reach the public encouraging the creation of Open Source Design communities. That scenario drives new demands, therefore, the industry and the services of the new social context move towards a Do-It-Yourself (DIY) paradigm.

In these circumstances, the search for non-commercial or research low-end 3D printers is growing. Inforçatti Neto (2013) has identified that the need to process small amounts of powdered raw materials along with precise control of such processes are specific demands at research centres and universities. Together with Freitas (2014), a technical solution was developed according to industrial polymer processing concepts, which lead to an interchangeable 3D print head based on a variable section single screw. The referred 3D print head is part of the Fab@CTI project, which possess a basic platform for moving in the x-y plane and allows mounting different extrusion-based print heads, whose objective is to promote studies with polymer compounding, biocompatible and biodegradable materials.

This document presents the design process used to develop a mini twin screw extruder and its mock-up, applied to the Fab@CTI platform as a continuation of the research line on novel design solutions for 3D printers. Created in the 1940s and 1950s, twin screw extruders were designed with the purpose of mixing highly viscous materials. Standard solution for melting and pressure build up at the time, single screw extruders tended to present throughput fluctuations and strong dependence of conveying on material properties, without any mechanism to facilitate material removal from the screw surfaces after the end of the process. In contrast, for its good mixing performance and self-cleaning property, co-rotating twin screw extruders are predominantly used in the plastic industry to prepare polymer blends, compounds and composites (Kohlgrüber, 2008; Teixeira et al, 2014; Eitzlmayr and Khinast, 2015).

The design of twin screw extruders is based on a modular principle, according to which different elements can be mounted to a core shaft. This allows the screw geometry to be changed providing different functional zones along the machine with optimized technical processes, which is very important for start up tests and process flexibility. Designing this type of equipment is much complex, because the interaction between geometric characteristics and operational conditions prevents the existence of models properly established to material behaviour in the extruder as well as a comprehensive simulation software capable to predict the most adequate screw configuration according to the

compounding tasks (Pearson, 1985; Kohlgrüber, 2008; Rauwendaal, 2013; Eitzlmayr et al, 2014). Therefore, as a complementary objective, the systematic design approach presented in this work provides some guidelines for pre-dimensioning the twin screw/barrel assembly based on a detailed research and adequation of the main literatures on TSE (Kohlgrüber, 2008; Rauwendaal, 2013), notoriously from the American and German schools.

2. TWIN SCREW EXTRUSION TECHNOLOGY

The extrusion process consists in converting raw material into a product of uniform shape and density by forced passage of the material through a die under controlled conditions. While the single screw extruders are primarily used for melting and pressure build-up, the twin screw extruders stand out for their good mixing performance and for propelling material independently of its properties, finding many applications in polymer, pharmaceutical and food industries (Kohlgrüber, 2008; Eitzlmayr et al, 2014).

In general, twin screw extruders are composed by a motor unity, twin screw/barrel assembly (which includes feed ports, screws, barrel sections, heaters and die) and controlling equipment (e. g. thermocouple, pressure transducers). Some machines present only one feed port located at the rear of the extruder in the first barrel section. However, it is possible to place additional feed streams along the barrel length, as the screws and barrel are both modular (Giles Jr. et al, 2004).

The main functional difference between twin and single screw extruders relates to the type of transport mechanism that takes place in the machines. In single screw extruders, material transport occurs due to frictional drag in the solids conveying zone and viscous drag in the melt conveying zone. Therefore, the conveying behaviour is strongly determined by the frictional and viscous properties of the material. In contrast, as the screws in the intermeshing extruders rotate, the volume between the flights (often referred as C-shaped chamber) stays confined due to the seal created between the two screws, which implies into a positive displacement type of transport. This way, throughput is proportional to the rotation speed of the screws (Pearson, 1985; Shah and Gupta, 2003; Rauwendaal, 2013).

When the shafts rotate in the same direction, the screws are called co-rotating and when they rotate in opposite directions, they are called counter-rotating. In addition, when the center line distance is less than the screw diameter, they are called intermeshing. The degree of positive displacement depends on how well the flight of one screw closes the opposing channel of the other, what in turn is related to the direction of rotation. The most positive displacement is obtained with closely intermeshing counter-rotation screws. High positive displacement, however, leads to poor mixing performance and for that reason co-rotating extruders are preferred for compounding applications (Shah and Gupta, 2003; C.A. Picard International, 2004; Giles Jr. et al, 2004; Rauwendaal, 2013; Eitzlmayr et al, 2014).

At the intermeshing region of co-rotating extruders, the flights tips have opposite velocity directions so that the material tends to be constantly pushed out, forming an open figure-eight pattern as it moves in the axial direction. When the co-rotating screws have a closely matching profile as show in Fig. (1), a sealing line forms along the flanks, and the continuous wiping movement of the screws creates the so-called self-wiping property. As can be seen in the cross section through the intermeshing region, this special geometry (often called fully wiped) provides a larger open area (Area II) relative to the obstructed area (Area I), which helps to avoid pressure peaks meaning that the screws can be designed with smaller clearances and operated with higher rotation speeds (Giles Jr. et al, 2004; Rauwendaal, 2013).

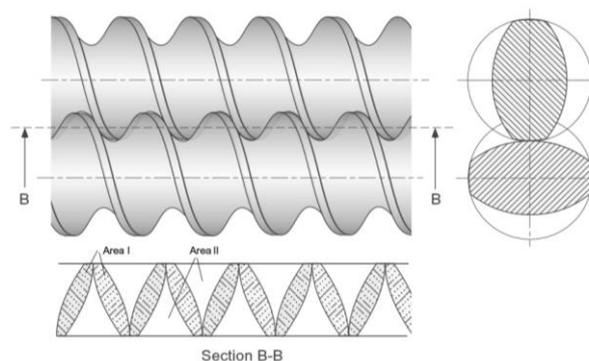


Figure 1. Flight geometry and cross-section through the intermeshing region in self-wiping co-rotating twin screw extruders (Adapted from Rauwendaal, 2013).

As mentioned before, the screws for co-rotating twin-screw extruders are usually designed in modules that can be arranged in various configurations, according to the processing tasks to be performed and the material to be processed. Therefore, the individual conveying and mixing elements are inserted onto the shafts to transmit operational torque, being also fixed to each other by applying a preload. Besides allowing high operational flexibility, modular design

favours fabrication, since screw geometry is generally too complex for conventional manufacturing processes (Kohlgrüber, 2008; Eitzlmayr et al, 2014).

Differently to what occurs in single screw extruders, in which channel depth varies along the axis length, channels tend to be constant in twin screws, especially when the self-wiping function is needed to be maintained. Moreover, single screw extruders operate flood-fed while twin screw extruders are starve-fed, so that there is less chance of agglomeration, resulting in improved mixing action in the extruder. Completely filled sections occur where restrictive elements, such as kneading blocks or left-handed elements, are placed (Rauwendaal, 2013).

2.1. Conveying Elements

Figure (2) shows the basic components used in twin screw extruders to transport the material that enters under many forms along the processing zones in its journey to the extrusion die. Number of flights, pitch, conveying direction and length characterizes them and the nomenclature is pitch/length, so that a 60/60 element has a 60mm pitch and its length is 60 mm (Giles Jr. et al, 2004; Kohlgrüber, 2008).

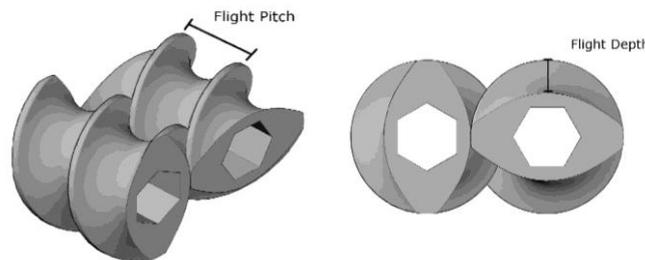


Figure 2. A pair of conveying elements (Adapted from Seem et al, 2015).

There are conveying elements available with one, two or three flights, however, intermeshing co-rotating extruders usually presents double-flighted elements. Single-flighted elements can build-up pressure more easily and provide more positive displacement, associated with less shear when compared with multiple flighted elements, however they tend to pulsate since there is only one product flow in comparison to three product flows in the case of double-flighted elements. Despite of generating more shear, triple-flighted elements can still be found in older extruders. The number of partial flows (NT) generated at the cross-section of the screws depending on the number of flights (Z), after Fig. (3), is given by Eq. (1) (Giles Jr. et al, 2004; Kohlgrüber, 2008):

$$NT = 2Z - 1 \tag{1}$$

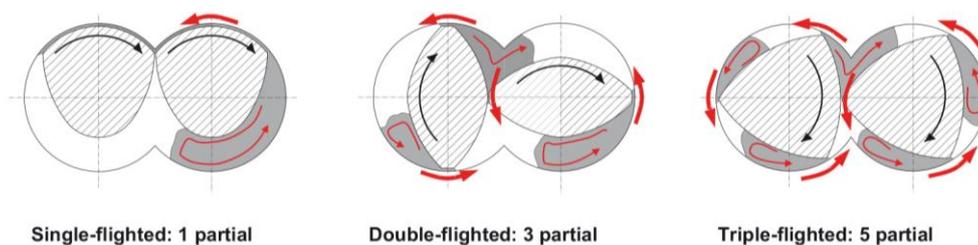


Figure 3. Number of partial flows in a twin screw extruder and mixing of the partial flows as a consequence of the leakage flow over the flight tip and in the intermeshing zone (Kohlgrüber, 2008).

The pitch is set according to the screw diameter (DE), so that in the feed zone it is usual to place large pitch elements with 1.5DE to 2DE, providing high conveying rate and low percent fill. Medium pitch conveying elements make one complete revolution about the screw every 1DE and are used for melting compression after large pitch conveying in the feed zone. Small pitch elements have normally 0.25DE to 0.75DE pitch, providing the highest percent fill without generating significant melt pressure and are used for pumping and heat transfer (Giles Jr. et al, 2004).

Screw direction determines if the conveying element transports material forward or rearward in the barrel. When the screw direction is opposite to the shaft direction of rotation, they are called right-handed and convey material forward. In left-handed elements, screw direction follows the shaft direction of rotation, therefore they convey material rearward (Giles Jr. et al, 2004; Kohlgrüber, 2008).

2.2. Mixing Elements

Successive transitions from large pitch conveying elements to small pitch elements cause repeated material compression and expansion as well as flow splitting at the tip of the flights, which provides some distributive mixing effect. However, to achieve good dispersive mixing effect, sufficiently high flow forces must be applied in order to cause pronounced shear and extension rates responsible for breaking agglomerates. Special screw elements are usually employed for this purpose, including kneading blocks, segmented mixers, toothed blocks, etc. (Giles Jr. et al, 2004; Kohlgrüber, 2008).

Kneading blocks, composed by prismatic discs made of self-wiping profiles, which are offset with respect to one another, are the most common mixing elements. Their function is to work the material by means of multiple deformations, providing an energy input that contributes to the melting process and distributive or dispersive mixing. These elements are characterized by length, staggering angle, number and width of discs and conveying direction. The nomenclature follows the following order: staggering angle/number or discs/element length. Therefore, a 45/5/60 kneading block has the second disc rotated 45° from the first with a total of 5 discs and a length of 60 mm (Giles Jr. et al, 2004; Kohlgrüber, 2008).

In general, for double-flighted elements, if the discs are offset at 60°, 45° or 60° with respect to one another, they can convey product forward and also build-up pressure. However, when the staggering angle of double-flighted discs is 90°, the block is considered neutral-conveying and must therefore be overrun, i.e., the product must be forced through them by conveying elements. Similar to conveying elements, there are right-handed blocks, which convey product forward and left-handed kneading blocks, which convey product rearward. Rearward conveying elements are used predominantly for back-pumping plastification zones. Figure (4) presents a pair of kneading blocks (Giles Jr. et al, 2004; Kohlgrüber, 2008).

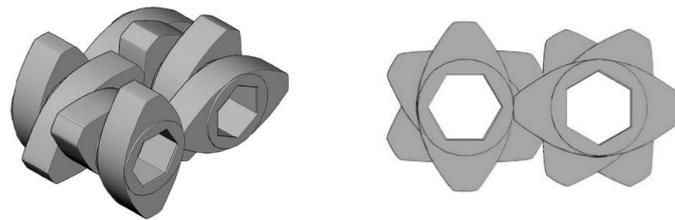


Figure 4. A pair of kneading blocks (Adapted from Seem et al, 2015).

As mentioned, distributive mixing takes place with flow splitting at the tip of the flights. A simplified mechanism for a single screw extruder is shown schematically in Fig. (5), in which a flow filament (also called “streamtube”) that begins at point “a” follows the root of the screw until it encounters the screw flight at point “b”. There, the “primary streamtube” is diverted around the shaft and ultimately reaches point “c” where a secondary streamtube splits off because of the leakage flow across the tip of the flight. This “secondary streamtube” passes through the same cycle as the “primary streamtube” and splits off a tertiary streamtube, so that more and more new partial flows form resulting in homogeneous mixing (Kohlgrüber, 2008). The mechanism can be applied to the elements of co-rotating twin screw extruders as well.

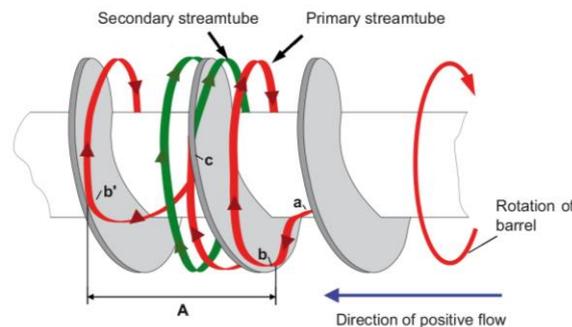


Figure 5. Division of flow in a single screw extruder – simplified presentation of the principle after Pawlowski (Adapted from Kohlgrüber, 2008).

In order to achieve dispersive mixing, flow forces that exceed a certain minimum value are required to break up agglomerates or to disperse liquid droplets. This is accomplished with kneading blocks, which create zones with almost

pure shear flow, in the gap at the flight tip and in the intermeshing region, and zones where extensional flow dominates before the flight tip and before the intermeshing region, as shown in Fig. (6) (Kohlgrüber, 2008).

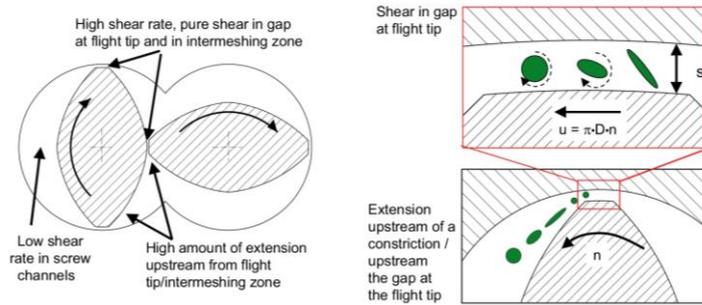


Figure 6. Shear flow and extensional flow in extruders (Kohlgrüber, 2008).

The probability that a particle is forced into the shear gap between the kneading disc and the barrel wall increases as the width of the disc increases. Therefore, kneading blocks with wide discs are better for dispersive mixing, while narrow kneading discs have a more distributive effect. In addition, the free space between adjacent discs tends to increase with increasing staggering angles so that conveying capacity decreases, until the neutral-conveying situation is achieved (Giles Jr. et al, 2004; Kohlgrüber, 2008).

3. SYSTEMATIC DESIGN APPROACH FOR A MINI TWIN SCREW EEXTRUDER APPLIED TO EXPERIMENTAL 3D PRINTERS

Figure (7) presents the main tasks comprising a systematic design approach for the twin screw/barrel assembly, which focus on determining the appropriate screw geometry and pre-dimensioning the main components (shafts, screw elements, barrel and die). The procedure is based on a mini twin screw extruder designed to process small amounts of powder material (around 100 g). According to Pahl et al. (2007), the design step where pre-dimensioning occurs (often referred as embodiment design) succeeds informational and conceptual design steps. Only after the verifications of the embodiment design step it is possible to detail the final features of the design, specify dimensions and tolerances, manufacturing processes and costs.

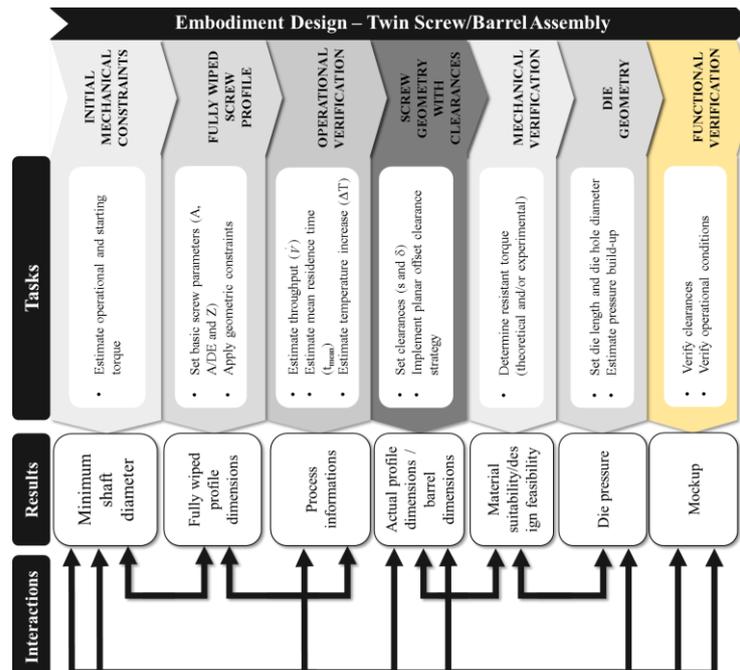


Figure 7. Systematic approach proposed for the embodiment design of the twin screw/barrel assembly, presenting the tasks involved in pre-dimensioning the main components, expected results and possible interaction between them.

Several different constraints can be considered at the first design steps, depending on the application of the system in development. The starting point considered in this paper is the torque provided to drive the screws. The necessary torque (T) for the application mentioned, considering maximum rotation velocity of 10 rpm, will be small. In addition, the constraints related to the materials and manufacturing processes available and the type of polymer to process were considered throughout all the embodiment design tasks. Having the allowable material stress (AMS), Eq. (2) can be applied to determine the minimum diameter of the shafts (D_{shaft}) where the screw elements are inserted (Beer et al, 2015):

$$AMS = \frac{16T}{\pi \times D_{shaft}^3} \quad (2)$$

3.1. Fully Wiped Screw Geometry

Design of the screw elements starts determining the basic fully wiped geometry and depends on three variables: external diameter (DE), center line distance (A) and number of flights (Z). In order to achieve the self-wiping property, tip and flank angles (KW0 and FW0) needs to be mathematically determined, and two geometric constraints must be attended. One relates the center line distance (A), external diameter (DE) and number flights (Z), presented in Eq. (3) and the other, relates core diameter (DI), center line distance (A) and external diameter (DE), shown in Eq. (4). The algorithm used to determine the angles and the equations that describe the fully wiped profile can be found in Kohlgrüber (2008) and in Rauwendaal (2013). The ratio of center line distance to external diameter (A/DE) determines the channel depth of the screw elements, having influence on the conveying capacity. This ratio must be at least 0,707 for double-flighted elements. Applying the previous equations, the center line distance and the core diameter can be determined.

$$\frac{A}{DE} \geq \cos\left(\frac{90^\circ}{Z}\right) \quad (3)$$

$$DI = 2A - DE \quad (4)$$

From the fully wiped profile, it is possible to check-up some operation parameters. The feed properties of the elements depends on the so-called free cross section surface (A_{free}), which corresponds to the difference between the barrel area and screws area, and can be easily determined mathematically, according to the equations presented in Rauwendaal (2013) or using CAD software's. The free volume (V_{free}) can be calculated multiplying the free area by the element length, what provides a good indication of the achievable filling ratio of the screw elements. The inherent throughput considering a bulk product with perfect wall slips can be calculated in Eq. (5), with the screw rotation speed (N) and element pitch (P), considering perfect slipping conditions. In real processes, most polymer melts adhere to the extruder walls, which in turns operates starve fed, so that the real throughput is one quarter of the inherent slip throughput (\dot{V}_{slip}) or less (C.A. Picard International, 2004; Kohlgrüber, 2008).

$$\dot{V}_{slip} = N \times P \times A_{free} \quad (5)$$

Material in the extruder experiences a residence time distribution based on the screw design, type of twin screw extruder, length to diameter ratio (L/DE), screw speed and feed rate. The average residence time (t_{mean}) is defined by Giles Jr. et al. (2004) as the ratio between the free volume (V_{free}) along total extruder length (L) and product throughput (\dot{V}), given in Eq. (6):

$$t_{mean} = V_{free} / \dot{V} = \frac{A_{free} \times L}{\dot{V}} \quad (6)$$

Friction and plastic deformation of the individual granules at the screw and barrel walls and between the granules themselves produces part of the heat needed to melt the material (Kohlgrüber, 2008). Having the power of the shafts and the mass flow rate, it is possible to use Eq. (7) to calculate the specific energy input (e), where N is the screw rotation velocity, η_A is the process efficiency (usually 0,76) and ρ is the material density. The average temperature

increase of the product in the extruder, without the die, is obtained simply dividing the specific energy input (e) by the specific heat at constant volume (c_v). From the average temperature increase, it is possible to know if more thermal energy is needed to melt the polymer.

$$e = \frac{T \times 2\pi \times N \times \eta_A}{\dot{V} \times \rho} \tag{7}$$

3.2. Screw Geometry With Clearances

It is essential to reduce the dimensions of the fully wiped screw profile to create the required clearances between the screws (s) and between the screws and the barrel (δ). In the absence of these clearances, the natural surface roughness of the screws and barrel may lead to “cold welding” and therefore to erosion and blockages. Besides, the clearances must be included considering that all production methods involve inherent production tolerances and that occasional irregularities in the heating process or torsional stress on the two shafts can lead to mutual shifting of the machine components. Moreover, process engineering aspects can also require particular clearances if, for example, intensive shear in the tip zones affects product quality (Kohlgrüber, 2008).

These different reasons for the need for clearances led to different strategies in their implementation. The most adequate strategy is called “planar offset”, which consists in orthogonally shifting the longitudinal section of the fully wiped profile inwards, at a distance equal to $s/2$, providing constant flank clearances between the screws. The method is fully described by Kohlgrüber (2008). Due to the complex interaction between the many variables, the procedure is usually carried out by a computer program. Figure (8) shows the planar offset clearance strategy.

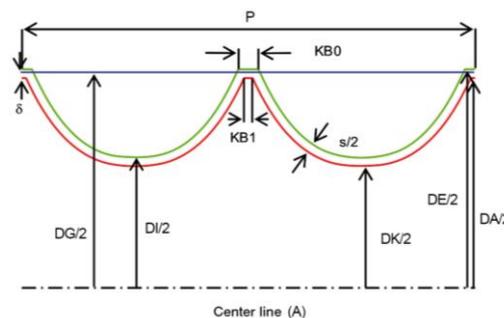


Figure 8. Geometric variables of a double-flighted screw profile, longitudinal section; Green: fully wiped contour, Red: offset contour, Blue: barrel wall (Adapted from Kohlgrüber, 2008).

Once implemented the planar offset method it is possible to determine the actual external and core diameters (DA and DK , respectively) and the actual tip and flank angles ($KW1$ and $FW1$, respectively) required to draw the screw profile considering clearances, which in turn is used to generate the three dimensional shape of the elements using a CAD software. It is important to notice that the cross section obtained through the planar offset method depends on the pitch (P) of the element. In general, the smaller the pitch, the smaller the tip angle ($KW1$) and, therefore, more pronounced the tip of the flight, as shown in Fig. (9).

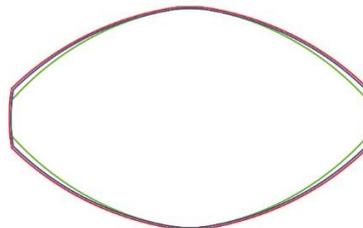


Figure 9. Comparison of profiles in which $A/DE=0,82$, $s/DE=0,01$, $\delta/DE=0,01$. Red: fully wiped, Blue: $P/DE=2$, Green: $P/DE = 0,4$ (Kohlgrüber, 2008).

Barrel geometry usually consists of a hollow rectangular or oval blank, with the hole formed by two intermeshing circles. The diameter of each circle forming the hole (DG) is equal to the actual screw diameter (DA) plus two times the clearance between the screws (s), and the distance between the center of the circles is equal to de center line distance

(A). Modular barrel sections normally have flanges on each end for alignment and connection to the next barrel (Giles Jr. et al, 2004). Having defined the geometry of the screw elements and the barrel, it is advisable to check if the provided torque will be able to overcome the resistant torque developed by the polymer being processed. It is known that most polymer melts present shear-thinning behaviour, which means that the viscosity and, by extension, flow resistance decreases with increasing shear rates (Bretas and D’ávila, 2010). The problem can be modelled looking to the polymer as a fluid confined in the annular space between an inner rotating cylinder, which represents the screw, and an outer stationary cylinder, which represents the barrel, as shown in Fig. (10). Since the inner boundary is moving with respect to the outer boundary, the fluid will be sheared (Rauwendaal, 2013).

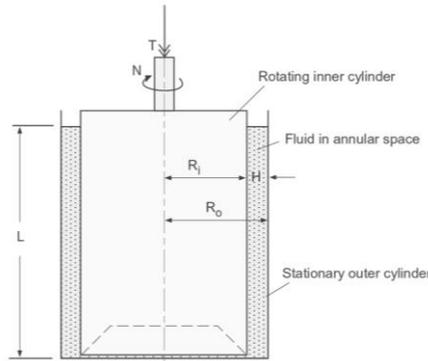


Figure 10. Co-axial cylinders: outer cylinder stationary, inner cylinder rotating (Rauwendaal, 2013).

The viscosity of the fluid generates tangential stresses, requiring a minimum torque to keep the shaft rotating. As long as the radial clearance (H) is small relative to the radius (R_i and R_o), the shear rate in the fluid will be the difference in velocity divided by the normal distance, so that the Eq. (8) can be used to determine the shear rate. Once the viscosity of the polymer (η) at a certain shear rate and temperature is known, it is possible to determine the resistant torque acting on the screw, according to the Eq. (9) (Rauwendaal, 2013).

$$\dot{\gamma} \cong \frac{v_o - v_i}{R_o - R_i} = \frac{2\pi \times R_i \times N}{H} \tag{8}$$

$$T_{res} = \frac{4\pi^2 \times R_i^3 \times L \times N \times \eta}{H} \tag{9}$$

The resistant torque can also be determined in practice, using a torque rheometer, capable of imposing conditions very close to those of twin screw extruders. In addition, with a torque rheometer it is possible to evaluate the rheological behaviour of polymer blends and composites. If the provided torque overcomes the estimated resistant torque in the most critical case, it is possible to select the elements that will configure the screw. Figure (11) shows the screw configuration developed in the reference example, composed by five processing sections, as indicated by Kohlgrüber (2008) for mixing purposes.

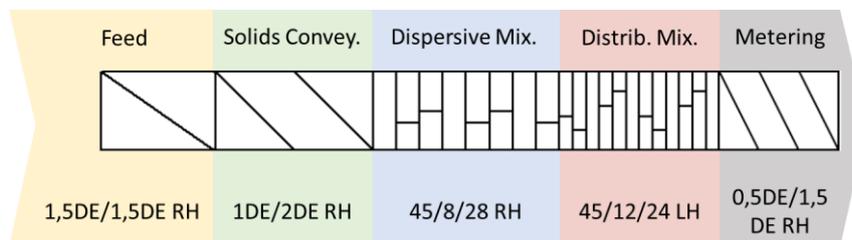


Figure 11. Screw configuration for mixing purpose developed in the reference example.

3.3. Die Design and mock-up of the mini twin screw extruder applied to experimental 3D printers

After the metering zone, the material is conducted to the die, responsible of shaping the extrudate and controlling its molecular orientation, which in turn has great influence on its physical properties and surface aesthetics of the product. Basic guidelines to die design include to avoid dead spots and increase velocity steadily along the flow channel, to

avoid abrupt changes in the channel geometry, to use small approach angles and to facilitate assembly and disassembly (Giles Jr. et al, 2004; Rauwendaal, 2013).

For simple circular dies, pressure at the end of the extruder barrel can be determined in function of the volumetric flow rate and material properties. On the other hand, the pressure at the end of the die is equal to the atmospheric pressure. If the orifice diameter is much smaller than the diameter of the extruder ($d_o \ll DE$), pressure drop at the die entrance can be estimated similarly to what occurs in capillary rheometry (Pearson, 1985). Kohlgrüber (2008) shows that the shear rate at the wall ($\dot{\gamma}_w$) developed by a shear-thinning fluid through a cylindrical pipe flow can be calculated in function of volumetric throughput, the power law index of the fluid (n) and of the die diameter (d_o), according to Eq. (10):

$$\dot{\gamma}_w = \frac{8(3n+1)V}{\pi \times n \times d_o^3} \quad (10)$$

Equation (11) establishes the balance of the wall shear forces caused by the shear stress at the wall (τ_w) against the pressure difference over the die length (L_{die}), which can be rearranged for direct determination of pressure drop (Δp) at the die in function of shear rate, as in Eq. (12).

$$\tau_w \times d_o \times \pi \times L_{die} = \Delta p \times \frac{d_o^2 \times \pi}{4} \quad (11)$$

$$\Delta p = \tau_w \times \frac{4L_{die}}{d_o} = \eta(\dot{\gamma}_w) \times \frac{3n+1}{n} \times 32 \frac{V \times L_{die}}{d_o^4 \times \pi} \quad (12)$$

Eitzlmayr et al. (2014) simplified Eq. (12) introducing a flow resistance parameter (K_p), that can be calculated using Eq. (13). Thus, pressure drop can be determined knowing the rheological behaviour of the material, die geometry and volumetric throughput, according to Eq. (14).

$$K_p = \frac{3n+1}{n} \times \frac{32}{\pi} \times \left(\frac{DE}{d_o} \right)^4 \quad (13)$$

$$\Delta p = \eta \times \frac{K_p}{DE^4} \times V \times L_{die} \quad (14)$$

From these fundamental concepts on TSE, a mock-up was generated using Fusion Deposition Modeling (FDM) technology. Figure (12-a) shows a preliminary study of the system regarding its geometry, cinematics and functionalities using a viscous material. The behaviour of the material in the twin screw/barrel assembly as expected from the theory validates the design approach. Further works includes mounting and evaluating the actual system in the experimental 3D printer platform, shown in Fig. (12-b), and using it to create new materials for 3D printing based on polymer composites and blends.



(a)



(b)

Figure 12. (a) Preliminary mock-up test, showing the screws and the viscous material as removed from the barrel; (b) Experimental Fab@CTI 3D printer platform.

4. CONCLUSIONS

Despite its major importance in polymer processing, few works on TSE are produced in Brazil, especially involving the design of the twin screw/barrel assembly components, what in part is explained by the geometries involved, their interaction with operational conditions and relatively complex manufacturing processes.

Twin screw extrusion is predominantly used when it is necessary to combine different materials to create polymer blends and composites with specific properties. In fact, this technology is finding applications not only in the traditional polymer industry but also in the development of novel materials applied to additive manufacturing, in order to mitigate anisotropy in the mechanical properties as well as to expand the applicability of components obtained by the most recent layer manufacturing technologies.

The systematic design approach presented in this work provides some guidelines for pre-dimensioning the twin screw/barrel assembly components. This procedure is the result of a detailed research and adequation of the main literatures on TSE (Kohlgrüber, 2008; Rauwendaal, 2013), notoriously from the American and German schools. It is also based on good design practices in order to preserve the desired self-wiping function of the screws as well as the close intermeshing with constant flank clearance. As a final task, the procedure suggests building a mock-up in order to verify the functionalities of the system. The results obtained from the preliminary tests with the mock-up validate the design approach and show that the device developed is suitable for its application as a polymer compounding mini extruder and 3D print head.

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