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DESIGN AND MODELLING OF INTERMESHING TWIN SCREW FOOD EXTRUDERS

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Summary. The paper presents fundamental knowledge of design and modelling of special type of food extruders, which can be useful for process design and practical application in feed and food sector. Mass flow teory and process phenomena are given to better understand action of these extruders in daily production.

Key words: twin screw extruders, extrusion-cooking, screws modeling, leakage

INTRODUCTION

Twin screw food extruders (extrusion-cookers) consist of two screws, placed in an 8-shaped barrel. In case of intermeshing extruders the flights of one screw sticks in the channel of the other screw. Because of this, the polymer cannot rotate with the screw, irrespective of the rheological characteristics of the material. This indicates the most important advantage of intermeshing twin screw extruders: the transport action depends on the characteristics of the material to a much lesser degree than in the case of a single screw extruder.

There are 4 main types of intermeshing twin screw food extruders:

- Tangential twin screw extruders are not closely intermeshing; they can be envisaged as a parallel connection of two single screw extruders with mutual interaction. A model based on three parallel plates is often used to describe this type of twin screw extruder. This model shows a strong resemblance to the two parallel plates model that is used for single screw extruders. This type of machine has clear advantages if very elastic materials have to be extruded. The screws can be arranged in two different ways, a mixing mode or a transport mode. All commercial tangential twin screw extruders are counter-rotating and used for special products.
- The closely intermeshing twin screw extruders, both counter-rotating and co-rotating, can best be modeled as series of C-shaped chambers. Due to the rotation of the screws these chambers transport the material from hopper to die, while interactions between the chambers occur via leakage flows. In general, these leakage gaps are larger in co-rotating machines than in counter-rotating ones. Due to the large resistance to back flow through the narrow gaps, these extruders posses a strong positive conveying character and their stability is large.

- The screws and the barrel of closely intermeshing twin screw extruders can also be conical. This has advantages for the feeding process if the material has a low bulk density. While passing through the extruder the chambers gradually decrease in size and compress the material. Moreover, conical screws provide a larger space for the bearings of the screws and the screws can easily be removed from the barrel.
- Depending on the exact geometry, self-cleaning co-rotating twin screw extruders can be described in two ways. They can be modeled as a series of C-shaped chambers with very wide leakage gaps or, which is more common, they can be considered to be constructed as continuous channels with some flow restrictions at regular intervals. This type of machinery imposes high shear forces on the material and to increase shear even further special shearing elements are common. Both screw configurations with two or three lobes or thread starts per screw exist. Two lobe screws possess a better conveying capacity and provide a higher throughput, three lobe screws have a larger mechanical strength and higher shear rates in the channel. Most modern machines have two lobe screws.

CLOSELY INTERMESHING TWIN SCREW EXTRUDERS

Closely intermeshing food extruders, both the co-rotating and counter-rotating ones have, in general, deeply cut channels and narrow leakage gaps. Their rotational speeds are generally low, due to the large shear forces on the material in the gaps. Therefore, the average shear level imposed on the material in the chambers is low. Self wiping extruders on the other hand, have shallow channels (especially if equipped with triple flighted screws). They operate with high rotational speeds and the transport efficiency (the amount of material transported per revolution) is lower than in closely intermeshing machines. In these machines the material is subjected to high average shear forces and the viscous dissipation is much larger than in the closely intermeshing machines.

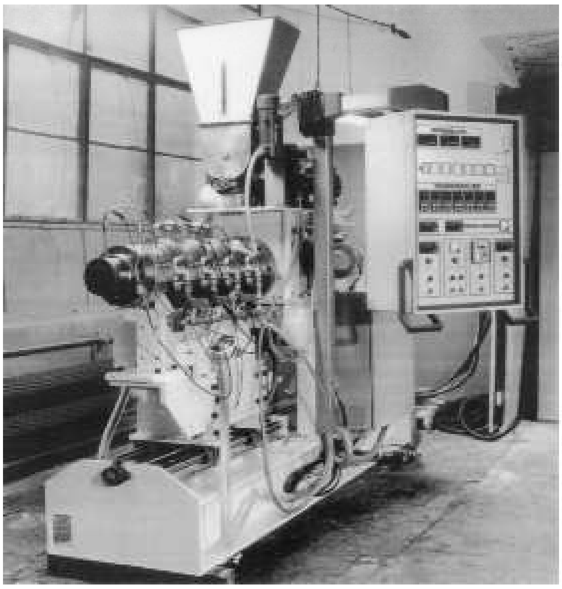

Fig. 1. Counter-rotating twin screw extrusion-cooker, type Valeurex, of modular construction of the plasticization unit (Polish, Dutch and Swedish design, result of the European Programme Eureka)

Conical twin screw food extruders have the advantage that the space provided for bearing is large. Moreover, by moving the screws axially, it is possible to compensate for wear of the screws. A disadvantage of this type of machines is that screw elements with different geometries are not easily interchangeable.

If the chambers of a closely intermeshing twin screw extruder are fully filled with material, the maximal throughput of a zone Q_{th} can be written as the number of C-shaped chambers that is transported per unit of time, multiplied by the volume of one such chamber:

$$Q_{th} = 2mNV. \quad (1)$$

Here N is the rotation rate of the screws, m is the number of thread starts per screw and V is the volume of a single chamber. In reality, the output of a twin screw extruder is, of course, smaller than the theoretical throughput, because the chambers are not completely closed. Four different kinds of leakage flows can be distinguished (see Fig. 2):

- A leakage (Q_f) through the gap between the flights and the barrel wall. This leakage shows clear parallels with the leakage that occurs in a single screw extruder. The gap through which this leakage flows is called the flight leak.
- A leakage (Q_c) between the flight of one screw and the bottom of the channel of the other screw. Because the flow through this gap resembles the flow in a calender this leak is called the calender leak.
- A leakage (Q_t) through the gap between the sides of the flights, which is called the tetrahedron leak. In principle, this leak is the only leak that leads from one screw to the other. In closely intermeshing counter-rotating twin screw extruders, this gap is generally very narrow. In self-cleaning counter-rotating twin screw extruders this gap is very wide and the major part of the material passes this gap regularly.
- A leakage (Q_s) through the gap between the sides of the flights, normal to the plane through the two screw axes. This leak is called the side leak. In its behavior this leak resembles the calender leak most.

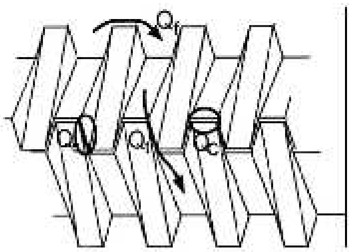

Fig. 2. Leakage gaps in a counter-rotating, closely intermeshing twin screw extruder

The throughput through the different leakage gaps partly consists of drag flow and partly of pressure flow. The pressure flow in its turn, is a consequence of the internal pressure build-up in the chambers and of the pressure that is built up at the die, resulting in the leakages:

$$Q_f = A_f N + B_f \frac{\Delta P}{\mu}, \quad Q_s = A_s N + B_s \frac{\Delta P}{\mu}, \quad (2)$$

$$Q_c = A_c N + B_c \frac{\Delta P}{\mu}, \quad Q_t = A_t N + B_t \frac{\Delta P}{\mu},$$

here the subscripts f, s, c and t stand for flight, side, calender and side gap. The total amount of leakage through a section of the extruder is the sum of the individual leakage flows. For a screw with m thread starts this can be written as:

$$\Sigma Q_l = 2Q_f + Q_t + 2m(Q_c + Q_s) = AN + B\frac{\Delta P}{\mu}, \tag{3}$$

in which ΔP is the pressure drop between two consecutive chambers, μ the viscosity and N the rotation rate of the screw. Numerical values for A and B and for the chamber volume V follow from the geometrical parameters of the screws only and are given in section 6.8.2 of this chapter. The real throughput of a pumping zone in a twin screw extruder, completely filled with polymer, can now be determined easily.

$$Q = Q_{th} - \Sigma Q_l = (2mV - A)N - B\frac{\Delta P}{\mu}. \tag{4}$$

For Newtonian liquids the use of dimensionless numbers for throughput and pressure drop leads to simple relations:

$$Q^+ = \frac{Q}{2mNV}, \qquad P^+ = \frac{\Delta P}{N\mu}. \tag{5}$$

Here ΔP is the pressure drop per chamber, caused by the pressure in front of the die and μ is the Newtonian viscosity. These two dimensionless groups for throughput and pressure are very powerful. When these groups are used, the characteristics for the completely filled pumping zone of twin screw food extruders are straight lines which are independent of viscosity and speed of rotation of the screws.

THE DIFFERENT ZONES

If a twin screw food extruder is stopped and opened, several zones can clearly be distinguished (Fig. 3). Depending on whether the extruder is fed with a solid or a liquid material two different situations occur. In case of a solid feed (which is generally the case in starch processing) the chambers near the feed hopper are more or less filled with solids. This material plasticizes, and a zone with only partly filled chambers can be seen. At the end of the screw, close to the die, the chambers are completely filled with material.

Fig. 3. The different zones in a twin screw extruder when fed with solid material a) solids transport, b) partly empty c) fully filled

If the extruder is fed with a liquid, like in some candy processes, the first part not necessarily needs to be partly empty. However, as will be explained later, for reasons of stability it is advisable to create a zone where the chambers are not fully filled. Especially the fully filled zone is very important for a proper functioning of the extruder. In this zone the pressure is built up, mixing and kneading mainly takes place and the major influence of viscous dissipation also occurs. In order to explain the existence of the fully filled zone, we will have to realize that the different zones in a twin screw food extruder cannot be viewed separately, but are interconnected. This can be shown by the throughput. The actual throughput of a twin screw extruder is determined by the feeding zone. What comes into the extruder here will also have to leave the extruder at the other end. Because the chambers are only partly filled, no pressure can be built up in this zone and the leakage flows will be limited to the drag component only. Under normal circumstances, the throughput of this zone is therefore independent of pressure at the die end of the extruder. In the last part of the extruder, where the pressure that is needed for squeezing the processed material through the die is built up, the chambers are fully filled with material, a pressure gradient is present and considerable leakage flows are dependant on this gradient.

As derived, the actual throughput through the completely filled zone is given by:

$$Q = 2mNV - \Sigma Q_l, \tag{6}$$

but the real throughput is determined by the feeding zone:

$$Q = 2m_v NV_v \varepsilon, \tag{7}$$

in which ε is the degree of filling of the chambers in this zone and the index v indicates that volume and number of thread starts of the screws relate to the geometry in this zone. Because of continuity, the difference between theoretical throughput and real throughput should equal the sum of the leakage flows:

$$\Sigma Q_l = 2N(mV - m_v V_v \varepsilon). \tag{8}$$

As the degree of filling ε does not depend on the final pressure and all the other parameters in the right term of this equation are also independent of pressure, it becomes clear that the sum of the leakage flows in a twin screw extruder must be independent of pressure. However, if the equation for the leakage flows is taken into consideration:

$$\Sigma Q_l = AN + B\frac{\Delta P}{\mu}, \tag{9}$$

the pressure drop per chamber is fixed and dependent on viscosity and geometry only. If geometry and viscosity would not change, the pressure gradient would be constant over the whole completely filled zone. Also a fixed pressure is built up in the die of the extruder, which depends on throughput, viscosity and die geometry. Therefore, within reason, there will be a point in the extruder at which the actual pressure becomes zero. Between this transition point of partly and fully filled chambers and the die there exist pressure gradients, there are leakage flows and the chambers are completely filled with polymer. Between this transition point and the feed hopper, there is no difference in pressure between consecutive chambers, the leakage flows are zero or only consist of drag components and the chambers are only partly filled with material.

The length of the completely filled zone is an important factor and for good process control, knowledge of the different parameters that influence the length of the completely filled zone is indispensable.

- If the extruder is filled with an iso-viscous liquid, the resistance of the die is doubled, the pressure in front of the die will also double, because the output remains constant.

However, the leakage flow is not influenced by the die pressure, so that the pressure gradient in the extruder remains constant. Ergo, the completely filled length increases.

- If the rotation speed is doubled, while keeping the specific throughput (throughput per revolution) constant the throughput will also double and consequently the die pressure will do so too. As the leakage flows also double, the pressure gradient will double and the length of the completely filled zone will remain the same.

If the viscosity is not constant, the ability to build up pressure is proportional to the viscosity. Changing consistency, for instance by gelatinization of the starch or by mixing with polyoles have their influence on the local pressure gradient and therefore on the filled length. Also the influence of the temperature in this scheme is based on a change in the local viscosity and, because of that, on pressure drop.

CO-ROTATING VERSUS COUNTER-ROTATING CLOSELY INTERMESHING FOOD EXTRUDERS

Both co-rotating and counter-rotating twin screw extruders can be modeled by means of a C-shaped chamber model. However, there are some differences. Because of reasons of construction (the screws must fit into each other) the tetrahedron gap in co-rotating machines is generally bigger than in counter-rotating machines. Moreover, the drag flow in the tetrahedron gap is in co-rotating extruders parallel to the direction of this gap. Where in counter-rotating extruders the direction of internal pressure generation favors the flow through the calender gap, in co-rotating machines this pressure generation favors the tetrahedron flow (Fig. 4). Since the tetrahedron leakage is the only leakage connecting the chambers on one screw with the chambers on the other screw the mixing between materials on the different screws is better in co-rotating machines. In counter-rotating extruders both drag flow and internal pressure generation favor the calender leak. Since in the calender gap the material is elongated and kneaded it can be concluded that counter-rotating extruders favor a good kneading action.

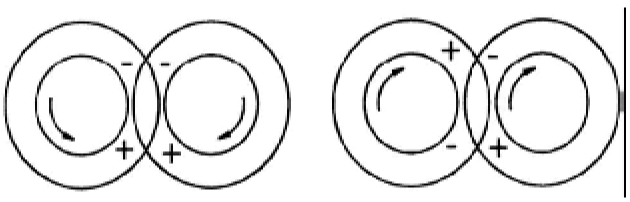

Fig. 4. Internal pressure generation in a counter-rotating a) and a co-rotating b) twin screw food extruder

THE MATHEMATICS OF EXTRUSION

For different types of extruders very sophisticated numerical models exist and computational fluid dynamics plays nowadays an important role in extruder modelling. Nevertheless, the different extruders can also be described with relatively simple models. Extensive description of these models can be found mainly in the literature on extrusion of synthetic polymers (rauwendaal, tadmor, janssen). Nevertheless, many features of these theories can also be used for food processing, and therefore some simple mathematical models with general validity are presented here.

The equations for the different leakage gaps are mathematically simple [Janssen, 1978]. The variables are defined in Figure 5.

For the tetrahedron gap in a counter-rotating twin screw extruder the following empirical equation exists:

$$Q_t = 0.0054\left(\frac{H}{R}\right)^{1.8}\left[\psi + 2\left(\frac{\varepsilon + \sigma\tan\psi}{H}\right)\right]^2 * \frac{\Delta P R^3}{\mu}. \tag{10}$$

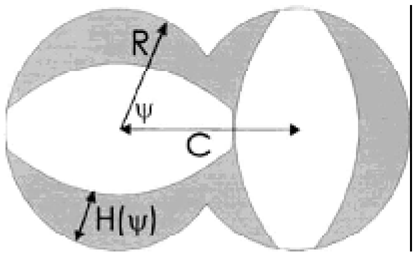

Fig. 5. Cross section through the screws

The derivation of the flight leakage is similar to that for the flight leakage in a single screw extruder:

$$Q_f = (2\pi - \alpha)R\left\{\frac{NB\delta}{2} + \frac{\delta^3}{6\mu B}\left[3\mu\frac{NB}{H^2}\left(\frac{B}{m} - B\right) + \Delta P\right]\right\}. \tag{11}$$

The equation for the calender leakage follows the classical derivation for the throughput of a two-roll calender, with the only difference, that the velocities of the two calender surfaces are different because of the different radii:

$$Q_c = \frac{4B}{3m}\left\{\frac{2m\Delta P\sigma^3}{6\pi\mu\sqrt{(2R - H)\sigma/2}} + N\pi(2R - H)\sigma\right\}. \tag{12}$$

For the side leak a semi empirical equation is used:

$$Q_s = \pi N(2R - H)(H - \sigma)(\varepsilon + \sigma\tan\psi) + \frac{m\Delta P(H - \sigma)(\varepsilon + \sigma\tan\psi)^2\cos\psi^2}{12\mu R\sin\frac{\alpha}{2}} * \tag{13}$$

$$\left[1 - 0.630\frac{\varepsilon + \sigma\tan\psi}{H - \sigma}\cos^2\psi + 0.052\left(\frac{\varepsilon + \sigma\tan\psi}{H - \sigma}\cos^2\psi\right)^5\right].$$

From the equations above it can simply be deduced that every leakage flow has two components, one drag component, proportional to the rotational speed and one pressure component, proportional to the pressure difference between two consecutive chambers and inversely proportional to the viscosity. The proportionality factors are only dependent on geometrical parameters. The only exception is the tetrahedron gap that only depends on pressure differences. The total amount of leakage can now be written as:

$$\sum Q_i = AN + B\frac{\Delta P}{\mu}, \tag{14}$$

in which, as can be seen from the equations, A and B are constants that only depend on the geometry of the screws.

Also the volume of a C-shaped chamber can easily be determined by straight forward calculations. Therefore we subtract the volume of the screw over the length of one pitch from the free volume of the barrel over the same length. The volume of the barrel follows from Figure 5:

$$V_1 = \left\{\left(\pi - \frac{\alpha}{2}\right)R^2 + \left(R - \frac{H}{2}\right)\sqrt{RH - \frac{H^2}{4}}\right\}S. \tag{15}$$

The volume of the screw root is :

$$V_2 = \pi(R - H)^2 S, \tag{16}$$

and the volume of the flight is:

$$V_3 = \int_{R-H}^{R} b(r) * 2\pi r \, dr. \tag{17}$$

For a screw with straight sided flights yields:

$$b(r) = B + 2(R - r) \tan \psi, \tag{18}$$

and the integral can be written as:

$$V_3 = 2\pi\left\{\left(RH - \frac{H^2}{2}\right)B + \left(RH^2 - \frac{2}{3}H^3\right)\tan\psi\right\}. \tag{19}$$

The total volume of one chamber can now be calculated from:

$$V = \frac{V_1 - V_2 - mV_3}{m}. \tag{20}$$

CONCLUSIONS

Twin screw food extruders can be divided into different classes: non-intermeshing (counter-rotating), closely intermeshing (counter- or co-rotating) and self wiping extruders (co-rotating). Especially the last two types have good pumping capabilities. Specific for twin screw extruders is the occurrence of a fully filled zone and a zone where the screws are only partially filled with material. The closely intermeshing food extruders are predicted for processing of “difficult” raw materials , e.g. fiber rich, which needs high shear and long residence time conditions. Properly used process parameters together with required screw configuration and plasticization unit allow to achieve complicated targets both in feed and food sectors.

Symbol list:

α	apex angle	-
Ψ	angle	-
ε	degree of chamber or channel filling	-
δ	flight gap width	m

κ	pressure correction factor for the intermeshing zone	-
σ	calender gap width	m
ξ	pressure factor for kneading elements	-
ϕ	screw angle	-
ε	tetrahedron width at the channel bottom	m
μ	viscosity	Pa.s
ΔP	pressure difference	Pa
ΣQ_l	total of leakage flows	m^3/s
A	geometry parameter	m^3
B	chamber width	m
B	geometrical parameter	m^3
c	distance between screw axes	m
D	screw diameter	m
f_d	drag flow correction factor single screw extruder	-
f_p	pressure flow correction factor single screw extruder	-
f_{ds}	drag flow correction factor self wiping extruder	-
f_{ps}	pressure flow correction factor self wiping extruder	-
f_{do}	drag flow correction factor non intermeshing extruder	-
f_{po}	pressure flow correction factor non intermeshing extruder	-
g	gravitational acceleration	m/s^2
H	channel depth	m
H_o	maximum channel depth	m
Je	Jeffreys number	-
L_f	filled length in axial direction	m
m	number of thread starts of one screw	-
N	rotation rate of the screws	1/s
P	pressure	Pa
P^*	dimensionless pressure	-
Q^*	dimensionless throughput	-
Q_f, Q_c, Q_t Q_s	leakage flow through the flight gap, calender gap, tetrahedron gap and side gap	m^3/s
Q_l	leakage flow	m^3/s
R	screw radius	m
S	pitch of the screw	m
U_x	wall velocity in the cross channel direction	m/s
U_z	wall velocity in the down channel direction	m/s
v	local velocity	m/s
V	volume of a C-shaped chamber	m^3
W	width of the channel	m
y	height coordinate in the screw channel	m
z	down channel coordinate	m
Z	length of the extruder channel	m

REFERENCES

Franz P., 1988.: Polymerreaktionen und reactives Aufbereiten in kontinuierlichen Machinen, in: Kunststofftechnik, VDI Verlag, Dusseldorf

Janssen L.P.B.M., 1978.: Twin screw extrusion, Elsevier, Amsterdam
Mościcki L, Mitrus M, Wójtowicz A., 2007.: Technika ekstruzji w przemyśle rolno- spożywczym, PWRiL, Warszawa.
Rauwendaal C., 1986.: Polymer Extrusion, Carl Hanser Verlag, Munchen
Tadmor Z. and Klein I., 1970.: Engineering Principles of Plasticating Extrusion, Van Nostrant Reinhold, New York

PROJEKTOWANIE I MODELOWANIE EKSTRUDERÓW DWUŚLIMAKOWYCH Z ZACHODZĄCYM NA SIEBIE UZWOJENIEM

Streszczenie. W artykule przedstawiono podstawową wiedzę w zakresie projektowania i modelowania specjalnego rodzaju ekstruderów, która może być przydatna do projektowania procesu produkcyjnego oraz praktycznego wykorzystania w czasie produkcji pasz i żywności. Podana teoria przepływu masy i dobór ślimaków ułatwi lepsze zrozumienie działania tych urządzeń w dziennej produkcji.

Słowa kluczowe: ekstrudery dwuślimakowe, ekstruzja, modelowanie ślimaków, wypływ wsteczny