DESIGN AND MODELLING OF SELF WIPING TWIN SCREW FOOD EXTRUDERS

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Summary. The paper presents fundamental knowledge of design and modelling of the most popular type of food extruders, which are used in feed and food sectors. Mass flow teory and process phenomena are given to better understand the action of these extruders and its application possibilities.

Key words: twin screw extruders, extrusion-cooking, screw elements, screw configurations

INTRODUCTION

An important difference between closely intermeshing and self wiping twin screw extruders is the way the screws fit into each other. In self wiping extruders the screw geometry is such, that in the plane through both screw axes there is a very close fit between both screws (Fig. 1). This requires a special geometry with, as a consequence, a very large tetrahedron gap between the "chambers". Due to this special character of most self wiping extruders the C shaped chamber concept has to be abandoned; a model based on continuous channels can better be used. Therefore, the self wiping extruder acts more as a drag pump than as a displacement pump. Each time when the material changes screw during its transport through a channel there exists a certain flow restriction. This can give an extra pressure built up, which is however in general very minute and for practical purposes this effect is often neglected.
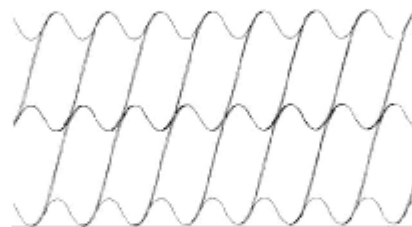

Fig. 1. Transport elements in a self wiping extruder

Screws of self wiping extruders consist of one, two or three thread starts. At an increasing number of thread starts the distance between the screw axes has to increase and as a consequence the maximum channel depth decreases, which in turn influences the maximal throughput per screw rotation. For this reason extruders with four or more thread starts are not common. Because there hardly exist any parallel planes close to each other in the geometry of self-wiping machine, a much higher rotational speed can be chosen for them than for closely intermeshing twin screw extruders. Combined with the shallow channels this leads to a high average shear level, which is in practice five to ten times higher than in closely intermeshing machines. The shear levels can be further increased by the use of so-called mixing or kneading elements. Changes in the angle between these elements determine the kneading action as will be seen later.

FUNDAMENTALS OF SCREWS' CONFIGURATION

Screw geometry

Because the screws have to fit closely in the plane through the axes, the degrees of freedom in screw geometry are very limited. Due to the requirement of close fitting in a cross section perpendicular to the axes, the surfaces of the screws must always (nearly) touch. This is shown in Figure 2.
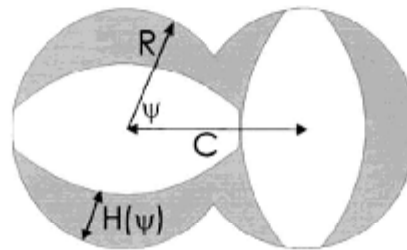

Fig. 2. Cross section through the screws

The channel depth as a function of the angle Ψ can be written in its most elementary form as:

$$H(\psi) = R(1+\cos\psi) - \sqrt{c^2 - R^2 \sin^2\psi}, \qquad (1)$$

where: c is the centre line distance. More complicated geometries exist with different radii of curvature to obtain geometries with a larger flight width or deeper channels. The cross section of the screw elements is the same as the cross section of the kneading elements. If building up extra pressure is required, elements with a more narrow pitch (pumping elements) are used. Nearly all self-wiping extruders consist of screws with separate screw elements and, depending on process requirements, different screw layouts can be constructed.

Transporting elements

The transporting elements in a self wiping extruder can, similarly to single screw extruders, be modelled by a cannel with a plate moving over it and their working is again basically by drag flow. The throughput can therefore be expressed as:

$$Q = \left(m - \frac{1}{2} \right) A N f_{d_s} - (2m-1) B \frac{\Delta p}{\mu} f_{\rho}. \qquad (2)$$

Where: A and B are geometrical parameters and m is the number of tread starts per screw. The most common value for m is two or three, where extruders with double tread starts (m = 2) have a larger throughput and triple start screws (m = 3) exert a higher shear on the material. The correction factors f_{d_s} and f_{ρ} account for the curvature in the channel.

It can be seen that also for self-wiping transport element the throughput can be divided into a drag component and a pressure component which, under the assumption of Newtonian rheology, are not interrelated.

Elements for building up pressure

By constructing screws with a large overlap in the intermeshing region the pressure building up abilities can increase considerably. In the limiting case the self wiping profile will be lost and C shaped chambers will emerge. Figure 3 shows these so called pressure building up elements. The pitch is generally chosen smaller than in transport elements. A model based on C shaped chambers leads to good results for this type of elements.
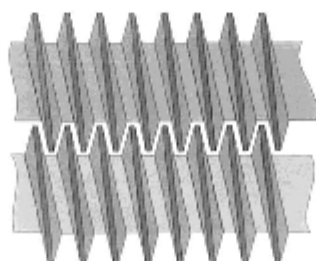

Fig. 3. Pressure generating elements

Kneading elements

The third type of elements present in self-wiping twin screw extruders is the kneading elements (Fig. 4). These elements consist of kneading discs that have the same cross-sectional shape as the transport elements. The angle between the individual kneading discs, the so called stagger angle, determines the kneading action. Stagger angles of 30, 60, 90, 120 and 150^0 are frequently used. The last two angles (120 and 150^0) are also sometimes referred to as -60 and -30^0. As a general rule it can be stated, that the larger the angle between the discs (30, 60, 90, 120, 150), the larger the kneading action, but this of course also results in a larger energy dissipation in the element. Also the pressure drop over the kneading element is dependant on the stagger angle. At moderate throughputs a kneading element with a stagger angle up to 60^0 can still build up some pressure, in all other situations a pressure is needed to transport the polymer through the element. This dependence on the stagger angle can be understood if we consider the kneading element as an interrupted screw flight.

At angles of 30 and 60^0 there exists a certain pumping action that depends on the rotational rate. At larger throughputs, the pressure drop over the element will decrease or, as stated, even become negative. In kneading elements with a stagger angle of 90^0 the pumping action is absent. This implies that the pressure needed to pump the polymer through the kneading element is independent of the rotation rate but proportional to the throughput. At stagger angles larger than 90 degrees the

kneading element acts as a screw element with reversed pitch. The transport elements in front of the kneading element have to pump against the reversed pumping action of the kneading element and high shear levels and large energy dissipation will be attained. Figure 5 shows an example of the pressure drop over the kneading elements as a function of the stagger angle at two different rotation rates at large and at small throughput. At increasing throughput the curves will be shifted upward, resulting in higher pressure drops at large stagger angles and a disappearing of the pressure generation at low stagger angles. For reactive extrusion the kneading elements have two functions: they improve the mixing and, as will be seen in the next paragraph, they increase the filled length in front of the element and therefore the hold-up in the extruder-reactor.
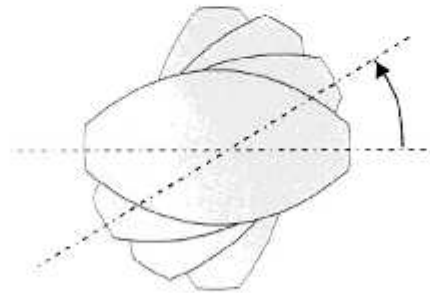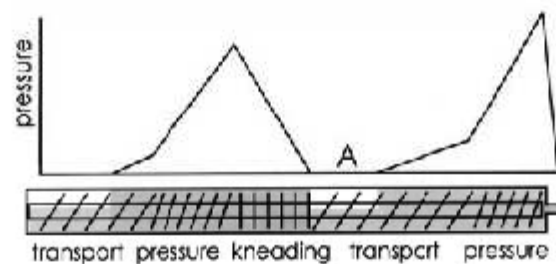

Fig. 4. Kneading elements

Fig. 5. A possible screw lay-out and the pressure profile. At location A material can be added or removed

The fully filled length

Similar to closely intermeshing twin screw extruders, in self-wiping extruders different regions can be distinguished where the screws are fully filled with material or only partially filled. Again in the fully filled region pressure is built up, in the partially filled zone the pressure gradient equals zero. This implies that a fully filled zone must be present before the die and before pressure consuming kneading elements. The length of these zones before the die (L_d) and before a kneading section (L_m) can be simplified to:

$$L_d = \frac{p}{\mu(AN - BQ)},$$
$$L_m = \frac{A'Q + B'N}{C'N - 2Q}.$$

(3)

The equations above can be used to quantify the influence of different extrusion parameters on the filled length. Striking is that the filled length in front of a kneading section is independent of viscosity. This is due to the simplification we have made in assuming an iso-viscous process: if the viscosity changes, a relative viscosity factor has to be introduced. The fact that the filled length is independent on the absolute value of the viscosity can be understood if we realise that both the pressure generating abilities of the transport elements as well as the pressure drop over the kneading elements are proportional to the viscosity: the absolute viscosity therefore has no influence on the length of the fully filled zone. Moreover the equations show that if we change the rotational speed and the throughput in the same way, or in other words we keep the relative throughput constant, the fully filled length does not change. If the throughput increases at constant rotation speed the filled length will increase and if the rotation rate increases at constant throughput the filled length decreases. Finally an increase of the stagger angle in kneading elements (increasing B') will also increase the filled length. Application of kneading elements with a more severe kneading action (larger stagger angles) will not only increase the kneading action in the elements themselves, but will also result in a larger filled length resulting in extra mixing. Figure 5 shows an example of the pressure profile in a screw, consisting of transport elements, followed by pressure built up elements, a kneading zone, transport elements and finally pressure building up elements before the die. At location A the material is pressureless and the channel is not necessarily fully filled. This location can be used for instance for devolatilization or for an easy feeding of an extra component. However, it should be realized that at increasing throughput the filling of the extruder increases and the pressureless zone will disappear

THE MATHEMATICS OF EXTRUSION

Because the working of self-wiping twin screw extruders is mainly based on drag in an open channel, the equations derived for single screw extrusion can be used. Combination of drag flow and pressure flow in one single channel leads to an equation for the throughput per channel:

$$Q = \frac{1}{2}WH_0U_x\, f_{d} - \frac{WH_0^3}{12\mu}\frac{dP}{dz}\, f_{p}.$$ (4)

Here: f_p and f_d are correction factors for the channel geometry and H_0 is the maximum channel depth. In case of rectangular screw channels the correction factors can be calculated analytically, for the complex geometry of self wiping extruders they can be approximated or calculated numerically. The number of parallel channels in a screw with m thread starts equals 2m-1. This leads to a throughput for a self wiping twin screw extruder of:

$$Q = \left(m-\frac{1}{2}\right)WH_0U_x\, f_{d} - (2m-1)\frac{WH_0^3}{12\mu}\frac{dP}{dz}\, f_{p}.$$ (5)

Apart from this, an extra pressure building up will occur in the intermeshing region. This can be expressed by means of a correction factor κ, that is a function of the relative flow area in the intermeshing region, leading to the final equation:

$$Q = \left(m-\frac{1}{2}\right)WH_0U_x\, f_{d} - (2m-1)\kappa\frac{WH_0^3}{12\mu}\frac{dP}{dz}\, f_{p}.$$ (6)

in practical situations this factor κ is close to one and its influence is often neglected. For shallow channels the shape factors f_{d} and f_{p} can be approximated by:

$$f_{dh} = \int_{-W/2}^{W/2} \frac{H(x)}{WH_0} dx,$$

and

$$f_{cp} = \int_{-W/2}^{W/2} \frac{H(x)^3}{WH_0^3} dx. \tag{7}$$

The pressure gradient in the fully filled zones can be calculated from the equation for the throughput and equals for an iso-viscous process:

$$\frac{\Delta P}{Z} = \frac{dP}{dz} = \left\{ \frac{WH_0}{2} (\pi ND\cos\phi) \, f_{cp} - \frac{Q}{2m-1} \right\} * \frac{12\mu}{\kappa WH_0^3 f_{dh}}. \tag{8}$$

As a consequence the fully filled length before the die in axial direction is :

$$L_f = Z\sin\phi = \frac{\kappa WH_0^3 f_{dh} P}{12\mu \left\{ \frac{WH_0}{2} (\pi ND\cos\phi) \, f_{cp} - \frac{Q}{2m-1} \right\}} \sin\phi \tag{9}$$

For kneading elements the pressure drop can be written as:

$$\Delta P = \mu\{AQ + \xi BN\}, \tag{10}$$

in which A and B are geometrical constants and ξ denotes the dependence of pressure on the stagger angle. ξ is negative for angles smaller that 90^0, zero for 90^0 and it increases with increasing stagger angle. If the pressure is zero after the kneading element, indicating a partially filled zone in that region, an expression for the filled length in front of the kneading element can be obtained:

$$Z = \frac{(2m-1)*(AQ+\xi BN)}{(2m-1)WH_0(\pi ND\cos\phi) \, f_{cp} - 2Q} \frac{\kappa WH_0^3 f_{dh}}{6}, \tag{12}$$

obtained from:

$$L_f = Z\sin\phi. \tag{13}$$

CONCLUSIONS

Nowadays twin screw food extruders became more popular due to their high efficiency and wide application. Specific for twin screw food extruders is the occurrence of a fully filled zone and a zone where the screws are only partially filled with material. The operating conditions and screw geometry determine the length of the fully filled zone and as a consequence the hold-up in the reactor. Completing screw geometry and process conditions, the operator can create products' properties accordingly to the expectations. To achieve that the extruder has to be equipped with many additional devices e.g. a conditioner, a steam generator, a chillier, liquid dozers and/or venting valves (see Fig. 6).
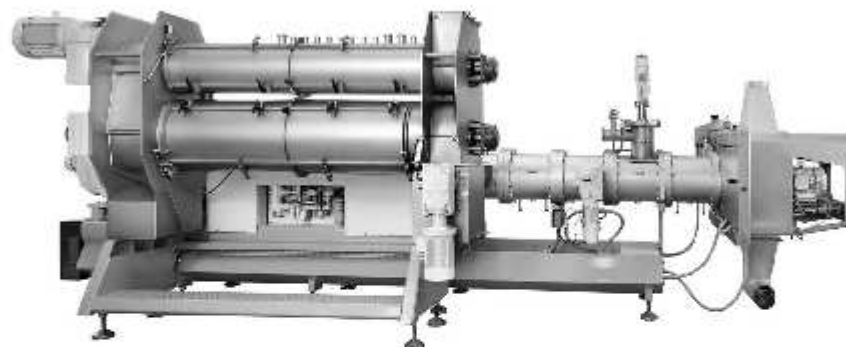
Fig. 6. Modern co-rotating twin screw food extruder

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

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PROJEKTOWANIE I MODELOWANIE EKSTRUDERÓW DWUŚLIMAKOWYCH Z UZWOJENIEM SAMOOCZYSZCZAJACYM

Streszczenie. W artykule przedstawiono podstawową wiedzę w zakresie projektowania i modelowania najpopularniejszych ekstruderów dwuślimakowych stosowanych w przemyśle rolno-spożywczym. Podana teoria przepływu masy i doboru geometrii ślimaków ułatwi lepsze zrozumienie działania tych urządzeń i ich wykorzystania w codziennej produkcji.

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