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DESIGN AND MODELLING OF SINGLE SCREW FOOD EXTRUDERS

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Summary. The paper presents fundamental knowledge of design and modelling of the most simple, inexpensive food extruders, which are still often used in feed and food sectors. Mass flow teory and process phenomena are given for better understanding action of these extruders and its possible application.

Key words: single screw extruders, extrusion-cooking, screw design, mass flow

INTRODUCTION

Nowadays food and feed sector is using different types of food extruders (extrusion-cookers), which are divided to a main division: single screw extruders and twin screw extruders. The most important difference between those two types of machines is the transport mechanism. A single screw food extruder consists of one screw rotating in a closely fitting barrel; the transport mechanism is based on friction between the material and the walls of the channel. If the material slips at the barrel wall, it is easy to envisage that it will rotate with the screw without being pushed forward. This makes these types of machines strongly dependent on the frictional forces at the wall and the properties of the processed material. Therefore, in the processing of natural polymers single screw extruders are less suitable for extrusion of mixtures with high water or high fat content. However, many food processes are possible in this (inexpensive) type of machine. An exceptional type of single screw extruder is the pin extruder (known in feed sector as expanders). In this extruder the screw has interrupted flights and it rotates in a barrel with stationary pins. The effect is twofold: due to the rotation of the screw a good mixing action can be achieved, and due to the increased resistance against slip the throughput is more stable than in ordinary single screw extruders. However, the pressure built up in this type of machine is rather poor. In some special types the screw not only rotates but also oscillates in axial direction.

Twin screw food extruders 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 (Fig. 1).

The single screw extruder (a) is the most common machine, if no problems in transport are envisioned. The working characteristics of this relatively inexpensive machine are strongly dependant on the material properties. Very short single screw extruders with high rotation rate are often used in starch industry for gelatinization purposes. The barrel can be equipped with grooves to increase the friction and to prevent the material from rotating with the screw.

Pin extruder and co-kneaders (b) have one single screw while the barrel is equipped with kneading pins and the screw flight is interrupted at the pin location In co-kneaders the screw rotates and oscillates giving a very good mixing action. In both types of extruders different pin geometries can provide different mixing actions. The pins can also be used for monitoring the temperature or as injection points. An important feature is that the pins prevent the material from rotating with the screw and therefore ensure a more stable operation than can be provided in an ordinary single screw extruder

In general it can be concluded that, because of the large shear forces in the channel

and the simple application of mixing elements, self wiping extruders are often used in processes where high shear is desirable. Their high shearing action is particularly convenient if intensive mixing or devolatilization is required. When working with thermoplastic starches, the low average shear in closely intermeshing extruders is an advantage because degradation of the starch results in deterioration of mechanical properties. Moreover, because of the low shear levels the heat generated by viscous dissipation is low, allowing for good temperature control. On the other side, self wiping extruders generally possess a better mixing action and higher throughput at comparable screw diameters.

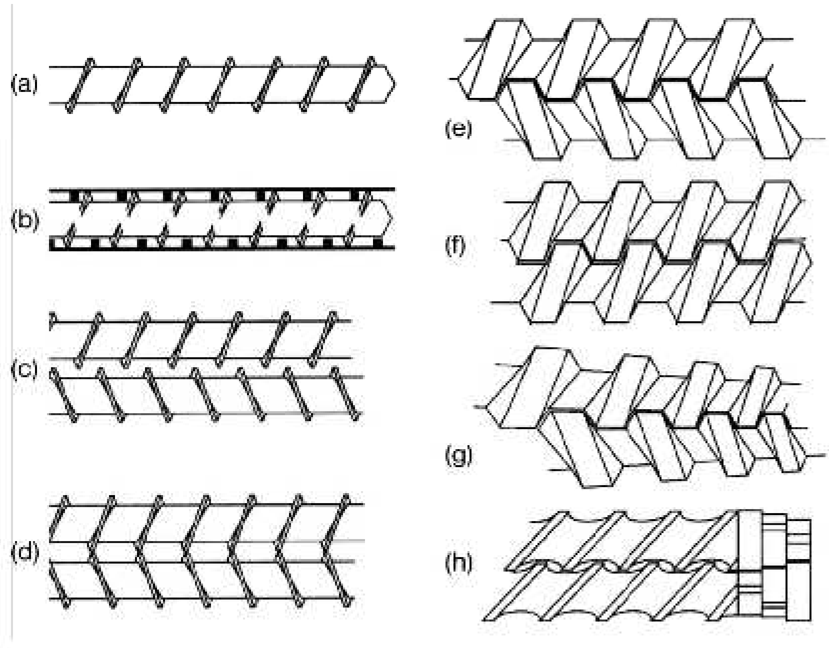

Fig. 1. Different types of extruders : a - single screw, b - co-kneader, c - non-intermeshing, mixing mode, d - non-intermeshing, transport mode, e - counter-rotating, closely intermeshing, f - co-rotating, closely intermeshing, g - conical counter-rotating, h - self wiping, co-rotating.

FUNDAMENTALS OF SINGLE SCREW EXTRUDERS

Single screw extruders can be used in processes where no slip at the wall occurs and where high shear during the process is not a problem. Their working mechanism and the modeling is well covered in literature and an extensive description can be found in various books [Rauwendaal ,1986; Tadmor and Klein, 1970]. The basis of the fluid flow in single screw extruders can also be generalized to other types of extruders. Therefore we introduce here a simple analysis based on Newtonian behavior of the liquid. For this analysis the channel of the screw is simplified into a flat plane geometry. The single screw extruder consists of a barrel containing a rotating screw. As a first step in the simplification we will keep the screw stationary and let the barrel rotate. The next step is to unwind the screw channel into a straight trough. Figure 2 shows the results. The rotation of the screw can now be transformed into the movement of a plate over the channel. The velocity of this plate is of course the circumferential velocity of the screw and equals πND, while its direction relative to the channel equals the screw angle ϕ. N is the rotation rate of the screw and D is the screw diameter.

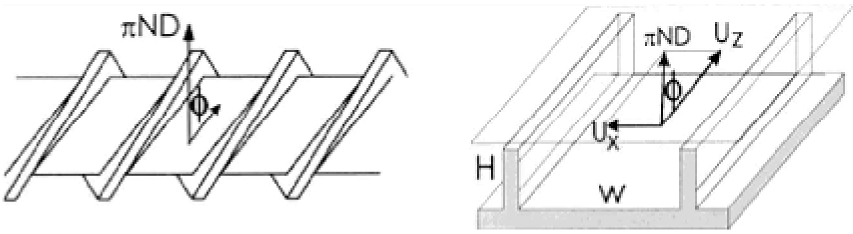

Fig. 2. The channel in a single screw extruder

The velocity profile in the down channel direction can, under the approximation of a Newtonian rheology easily be calculated and, after integration, the throughput follows:

$$Q = AN - B\frac{\Delta p}{\eta}. \quad (1)$$

Where: N is the screw rotation rate, Δp is the pressure difference over the zone and η is the viscosity. A and B are parameters that only depend on the screw geometry. The interesting aspect of this equation is that the influence of the rotation rate (the drag flow) and the influence of the pressure (the pressure flow) are uncoupled (Fig. 3).

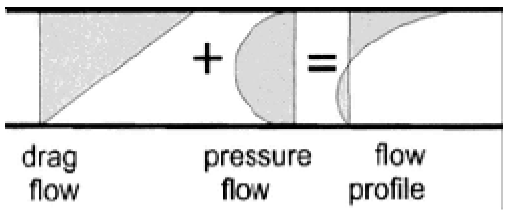

Fig. 3. Superposition of drag flow and pressure flow in a single screw extruder

If the flow across the flights of the screw can be neglected (which is generally the case for the hydrodynamics in single screw extruders) the velocity profile in the direction transverse to the channel is given by:

$$v_x = 3U_x \frac{y}{H} * \left(\frac{2}{3} - \frac{y}{H}\right) \tag{2}$$

and this profile, in combination with the down channel direction shows a helical path of the fluid elements through the channel.

The cross channel flow forms a circulatory flow as sketched in Figure 4. The center of circulation, where v_x equals zero, lies at 2/3 of the channel height. This cross channel profile must of course be combined with the down channel profile; the cross channel flow should be superimposed on the flow in the channel direction. As a result the polymer elements follow a helical path through the channel. The center of rotation of this helical flow lies at 2/3 of the channel height. Particles in this location follow a "straight" line through the channel without being interchanged with particles at other locations. Therefore these fluid elements will never approach the wall closer than 1/3 of the channel depth if no mixing elements are used in the screw design. This will appear to be particularly important when considering heat transfer and thermal homogenization in processes with viscous dissipation.

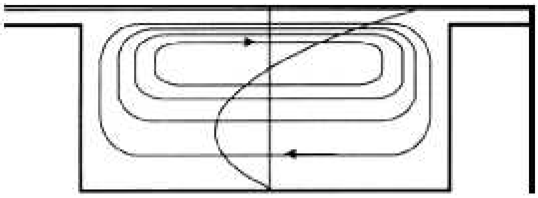

Fig. 4. Rotating flow in the cross–channel direction

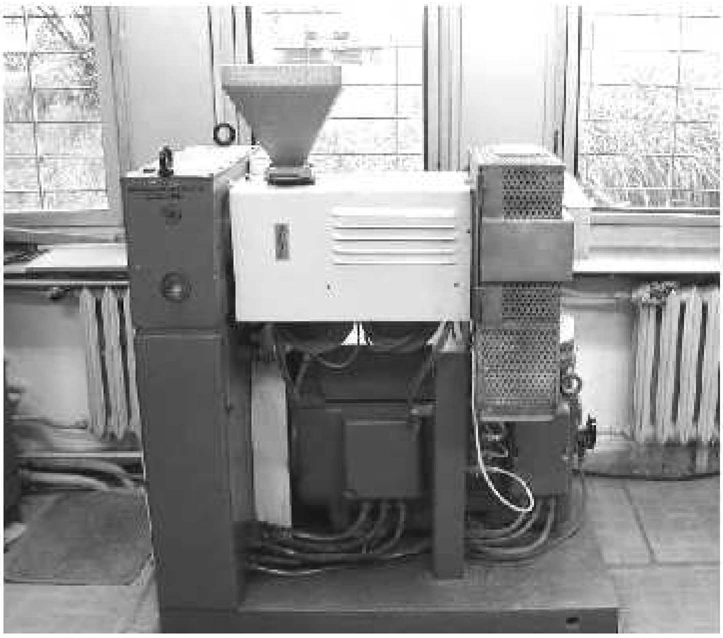

Fig. 5. Single-screw extruder, type TS-45 produced by ZMCh Metalchem Gliwice, equipped with an electric heating system and a water-air cooling system for the barrel. (Mościcki design)

PIN EXTRUDERS

A particular type of single screw extruder that can be used for feed components processing is the pin extruder. This type of extruders has two different designs, one with stationary pins and a simple rotating screw and interruptions of the flights, called the expander and one with a rotating and axially oscillating screw, generally known as a co-kneader. Though discovered in 1945 and commonly used in industry, its application is far ahead of theoretical understanding.

Also the co-kneader consists of a single screw with interrupted flights. Its working principle is based on the rotation and axial oscillation of the screw, causing transportation and mixing. The mixing is enhanced by stationary pins in the barrel. During one passage of the pin, the material is subjected both to high shear stress and to reorientation. The dispersive mixing process is promoted by the local weaving action of the pins and screw flights, where the distributive mixing is enhanced by the reorientation that is introduced by the pins.

The expander extruder (Fig. 5) is a relative simple machine. The function of the pins is two-fold, providing a more stable throughput and improving mixing. Due to the stationary pins, slip at the wall is prevented and the material can not rotate with the screw. This provides a more stable throughput. The mixing is increased relatively to an ordinary single screw extruder. Pin extruders provide both distributive and dispersive mixing. The distributive mixing is caused by the geometry of the screw flights. The interruptions in the flights divide material in the screw channel into two streams. After the following interruption of the screw flight the streams recombine partially and the material is divided again. The kneading pins provide also a rearrangement of the stream lines. Due to these two effects the distributive mixing of a pin extruder is very good and the distributive mixing process requires relatively low energy.

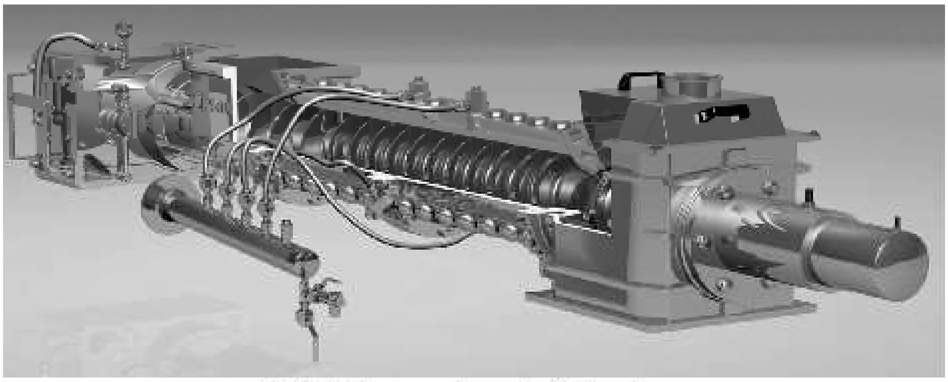

Fig. 5. Modern expander used by feed producers

By the rotating and oscillating movement of the screw in a co-kneader, the screw flights slide along the pins and barrel. This results in high shear stresses and disperse mixing. It also leads to good self-cleaning properties which is much less the case in expander extruders.

The temperature can be controlled by the thermostated barrel and screw. The large area/volume ratio as well as the radial mixing contribute to good heat transfer capacities. These characteristics make pin extruders well suited for processes, where good dispersive mixing is required, a disadvantage is that the relative high shear can easily give rise to degradation of the starch. Due to the large interruptions of the flights it is not possible to use this machine for pressure building-up. If at the end of the line pressure is needed, a normal single screw extruder is generally placed behind the pin extruder. The mixing mechanism in the co-kneader is rather complex.

THE MATHEMATICS OF SINGLE SCREW EXTRUSION

For food extruders very sophisticated numerical models exist and nowadays computational fluid dynamics plays an important role in extruder modelling. Nevertheless, the single screw extruders can also be described with relatively simple models. Extensive description of these models can be found mainly in the literature for extrusion of synthetic polymers (Rauwendaal, 1986; Tadmor and Klein, 1970). Nevertheless, many features of these theories can also be used for food processing (Moscicki at al, 2007), and therefore some simple mathematical models with general validity are presented here.

According to the well-known theory, the rotation of the screw can be transformed into the movement of a plate over a flat channel. The velocity of this plate is of course the circumferential velocity of the screw and equals πND, while its direction relative to the channel equals the screw angle ϕ. N is the rotation rate of the screw and D is the screw diameter.

The movement of the plate has a component in the down channel direction and a component in the cross channel direction; both drag the liquid along and introduce flow profiles with components parallel and perpendicular to the direction of the channel.

$$U_z = \pi ND \cos\phi$$
$$U_x = \pi ND \sin\phi \tag{3}$$

The flow in the down channel direction can be calculated from a force balance:

$$v_z = \pi ND\cos\phi \frac{y}{H} - \frac{H^2}{2\mu}\frac{dP}{dz}\left\{\left(\frac{y}{H}\right) - \left(\frac{y}{H}\right)^2\right\}, \tag{4}$$

where: dP/dz denotes the pressure gradient in the down-channel direction. A closer look at this equation reveals that the right hand side consists of two terms. The first part (apart from geometrical parameters) only depends on the rotational speed and the second part is a unique function of the pressure; so the effects of screw rotation and pressure can be separated. This is shown in Figure 3. The actual flow profile is a superposition of the (linear) drag flow and the (parabolic) pressure flow. However, strictly speaking this separation is only valid for Newtonian liquids.

From the velocity profile in the down channel direction the throughput of the pump zone of a single screw extruder can be obtained by integration:

$$Q_v = W\int_0^H v(z)\,dy = \frac{WH}{2}\pi ND\cos\phi - \frac{H^3 W}{12\mu}\frac{dP}{dz}. \tag{5}$$

Also in this equation the effects of drag flow and pressure flow can be separated; the drag flow is proportional to the rotational speed of the screws and the pressure flow is proportional to the ratio of pressure gradient and viscosity.

That equation is often written as:

$$Q = \frac{1}{2}\pi^2 ND^2 H(1-a)\sin\theta\cos\theta, \tag{6}$$

θ is the flight angle and a is the throttle coefficient that signifies the ratio between the pressure flow and the drag flow:

$$a = \frac{H^2 \Delta P \tan\theta}{6\mu(\pi ND)L}. \tag{7}$$

In the analyses above the width of the flight is neglected and it can be shown that this simplification has no significant influence on the final outcome.

For the transverse direction of the channel too, an analogous calculation can be set up and, if the flow across the flights of the screw can be neglected (which is generally the case for the hydrodynamics in single screw extruders) the velocity profile in the direction transverse to the channel can easily be calculated:

$$v_x = 3U_x \frac{y}{H} * \left(\frac{2}{3} - \frac{y}{H}\right), \tag{8}$$

and this profile, in combination with the down channel direction shows a helical path of the fluid elements through the channel.

The cross channel flow forms a circulatory flow as sketched in Figure 4. The center of circulation, where v_x equals zero, lies at 2/3 of the channel height. This cross channel profile must of course be combined with the down channel profile; the cross channel flow should be superimposed on the flow in the channel direction. As a result the polymer elements follow a helical path through the channel. The center of rotation of this helical flow lies at 2/3 of the channel height. Particles in this location follow a "straight" line through the channel without being interchanged with particles at other locations. Therefore these fluid elements will never approach the wall closer than 1/3 of the channel depth if no mixing elements are used in the screw design. This will appear to be particularly important when considering heat transfer and thermal homogenization for reactions where a large amount of reaction heat is released.

Correction factors

Strictly speaking, equations 2 and 3 are only valid for straight extruder channels of infinite width. To account for the curvature of the channel and the finite width, correction factors can be used and equation 3 can be written as:

$$Q_v = \frac{WH}{2}\pi ND\cos\phi . f_d - \frac{H^3W}{12\mu}\frac{dP}{dz}.f_p. \tag{9}$$

The correction factors follow from an analytical solution of a two dimensional stress balance:

$$f_d = \frac{16W}{\pi^3 H}\sum_{i=1,3,5}^{\infty}\frac{1}{i^3}\tanh\left(\frac{i\pi H}{2W}\right), \tag{10}$$

$$f_p = 1 - \frac{192H}{\pi^5 W}\sum_{i=1,3,5}^{\infty}\frac{1}{i^5}\tanh\left(\frac{i\pi W}{2H}\right).$$

For practical purposes (H/W < 0.6) these factors can conveniently be approximated by: (11)

$$f_d = 1 - 0.57\frac{H}{W},$$

$$f_p = 1 - 0.62\frac{H}{W}.$$

Basically these correction factors can be used not only for single screw extruders but for all types of extrusion processes.

CONCLUSIVE REMARKS

During food extrusion processing the consistency of the material changes from solids to a highly viscous dough with some polyole added. This requires good pumping abilities, preferably independent of viscosity and slip. If the slip is limited single screw extruders can do a good job, especially if the barrel wall is equipped with grooves to increase friction and prevent slip. Generally, a more stable process can be obtained in (more expensive) twin screw extruders.

A special type of single screw extruder is the pin extruder (expander). This type of extruder is provided with mixing pins through the barrel wall and the flights of the screw are interrupted. This extruder provides a very good mixing action, good transporting characteristics but poor abilities to build up pressure. Especially when extensive micro-mixing is required this extruder is a good alternative, although care has to be taken that no significant degradation occurs.

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_{dn}	drag flow correction factor non intermeshing extruder	-
f_{pn}	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 JEDNOŚLIMAKOWYCH

Streszczenie. W artykule przedstawiono podstawową wiedzę w zakresie projektowania i modelowania najprostszych, niedrogich ekstruderów, które są jeszcze stosowane przez przemysł rolno-spożywczy. Podana teoria przepływu masy i doboru geometrii ślimaków ułatwi lepsze zrozumienie działania tych urządzeń i ich wykorzystania w codziennej produkcji.

Słowa kluczowe: ekstrudery jednoślimakowe, ekstruzja, konstrukcja ślimaków, przepływ masy