Kohlgrüber (Ed.)
Co-Rotating Twin-Screw Extruders:
Applications
Co-Rotating Twin-Screw Extruders: Applications
The twin-screw extruder is of great importance in various industrial sectors, such as in the plastics, food, and pharmaceuticals industries. The editor published a book on this subject in late 2007 as both English- and German-language editions, the former of which was called simply “Co-Rotating Twin-Screw Extruders”. In the meantime a considerably extended and updated 2nd German edition of the book (Der gleichläufige Doppelschneckenextruder) was published in 2016. The preface of this German edition translated into English is appended below. About half of this German edition, with a focus on the fundamentals of co-rotating twin-screw extruders, was published in English as “Co-Rotating Twin-Screw Extruders: Fundamentals” in 2019. This current book corresponds to the second half of the German edition, focusing on the applications and functional zones of these extruders. In particular, the following focal points are described:

- Solid transport and melting
- Degassing of polymer melts
- Scale-up and scale-down
- Extruder technology, series, housing variants, materials
- Compounding in practice, color masterbatches
- Reactive extrusion, food extrusion, pharmaceutical applications

The editor would like to thank all the section authors, especially for their English translations. My thanks also go to Mr. Thomas König, who has clarified technical terms and also carried out an overall review. Dr. Smith from Carl Hanser Verlag has again made a considerable contribution to the success of this English edition and has given the editor exceptional support!

Klemens Kohlgrüber, September 2020

Preface to the Second German Edition

The 50th anniversary of the “twin-screw compounder (ZSK)” was the occasion for the first edition of this book. Therefore, only authors of the companies Bayer (licensor, Chapter 1) and Werner & Pfleiderer (today Coperion, licensee) were involved.
The elaboration of the first edition took place under considerable time pressure because, after the first idea for this book, it should appear on the occasion of the Plastics and Rubber Fair “K 2007”.

For the present edition it was my intention as editor to incorporate especially the following improvements and extensions:

- The participation of different companies and universities.
- A greater involvement of technical topics.
- Naturally the consideration of the further developments that have been made in the meantime (concerning screw geometries, calculation approaches, applications, ...).
- The basics of the extruder technique and the process descriptions by means of models should be described in more detail.
- Especially application-oriented practical examples should be incorporated to a larger extent.
- The contributions should be better coordinated.

This has succeeded now in many points of the present second edition. The reader may decide himself on the qualitative improvements. The extent has grown because of the number of contributions and by the more detailed depiction of the basics. The book should now be readable for apprentices in technical professions and simultaneously represent a benefit for experts due to the described applications. Some chapters are partly overlapping; this has been done intentionally. Due to different authors with different explanations regarding the same facts, some topics will become clearer. When coordinating the contributions I have tried to ensure that largely the same denominations and formula symbols have been used. The description of a topic and the interpretation of findings have been the focus of the respective author. In particular cases, a fact can be seen differently by different authors, for example the evaluation regarding usefulness of models (for more details please see Section 1.4). For this reason I refrained from the original intention to write a summary for each contribution. This could lead to an assessment being “counterproductive” in the sense of cooperation.

I would like to take this opportunity to offer heartfelt thanks to all authors for their contributions! I thank Mr. Lechner for the coordination of the contributions of Coperion.

My thanks go to all those who contributed with their comments on improvements and detailed definitions. Furthermore I would like to thank my daughter Kristina for the review of my contributions.

Here my special thanks are due to Ms. Wittmann of the publisher Hanser! She always accompanied the “book project” from the preparation phase until the end and gave valuable contributions for designing the book.

Klemens Kohlgrüber, May 2016
Dr. Klemens Kohlgrüber completed a metalworking apprenticeship, after which he obtained two years of professional experience. He then undertook further education in Cologne to become a mechanical engineering technician, and then studied in Wuppertal to become a mechanical engineer, followed by a licentiate degree and doctorate from the RWTH Aachen University (each in Germany). From 1986 to 2015 he was employed at Bayer AG, in roles including leading the group on high-viscosity, mixing, and reactor technology. In parallel and over many years he has lectured on compounding/preparation of polymers to master’s students in chemistry at the University of Dortmund, Germany. Also for many years, he has led the working group on high-viscosity technology at the Forschungsgesellschaft Verfahrenstechnik (German Research Association for Process Engineering) and was a member of the Association of German Engineers (VDI) advisory board on plastics preparation/compounding technology. He leads annual VDI seminars on the topic of extruders.
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1.1 Transport of Solids into and in the Extruder, Feed Limits

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During compounding, mainly solids, and in rare cases liquids or melts, are fed into the feed hopper located at the beginning of the twin-screw extruder. Furthermore, after the melting zone, additional solids can be fed into the extruder via side feeding units and liquids and gases can be injected via injection nozzles.

Twin screw extruders can be operated either starve fed or flood fed.

When run starve fed, less product is fed into the twin-screw extruder via the feed hopper than the screws can convey. Therefore, the feed zone is not completely filled with product.

Advantages include, for example, better recipe accuracy when dosing several components separately and higher flexibility due to the variable energy input caused by the variable throughput/speed ratio (filling degree) [1].

In flood fed operation, the extruder is operated with a fully filled feed hopper. This means that the screws convey as much product as their conveying capacity.

This section is limited to the description of the processes in the solids conveying zone at the beginning of the twin-screw extruder in starved feed operation, as co-rotating twin-screw extruders, unlike single-screw extruders, are generally operated in a starved feed condition.

As shown in Table 1.1, the solids to be dosed can be differentiated according to their particle shape and their melting behavior.
Table 1.1 Classification of Solids Fed into the Twin-Screw Extruder and Typical Examples

<table>
<thead>
<tr>
<th>Particle shape</th>
<th>Melting behavior Non-melting</th>
<th>Melting behavior Low melting</th>
<th>Melting behavior Melting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellet</td>
<td>Filler-masterbatches</td>
<td>Polymers</td>
<td></td>
</tr>
<tr>
<td>Powder</td>
<td>Filler, pigments</td>
<td>Waxes</td>
<td>Polymers</td>
</tr>
<tr>
<td>Flakes</td>
<td>Waxes</td>
<td>Polymers</td>
<td></td>
</tr>
<tr>
<td>Fiber</td>
<td>Glass, carbon</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*) melting point lower, ca. 100 °C

Usually, solids with different particle shapes and melting behavior are fed simultaneously into the twin screw extruder, e.g. melting polymer granulates together with non-melting filler powder and low-melting wax.

1.1.1 Characteristic Values and Calculation Possibilities

In order to determine the required speed range for a required throughput when operating in starved feed mode or to determine the maximum possible throughput at a given screw speed, it is necessary to know the solids conveying capacity. The intake capacity depends on the free cross-section between the screw elements and the barrel, the screw pitch, the bulk density of the solid, the conveying efficiency, and the screw speed.

\[
\dot{M}_F = A_{\text{free}} \cdot T \cdot \rho_S \cdot \varphi \cdot n
\]  

(1.1)

However, this approach only applies to simple bulk solids without feed limitation with linear throughput/screw speed behavior (cf. Figure 1.3).

In co-rotating twin-screw extruders with axially open screw channels, the conveying efficiency in Equation (1.1) depends on the friction conditions of the solid with the inner cylinder surface and the screw surface as well as the inner friction of the solid. To achieve the highest possible conveying efficiency, the circumferential force between the cylinder surface and the solid must be as high as possible and the circumferential force between the solid and the screw as low as possible. This can be illustrated using a rotating threaded rod (screw) with a threaded bushing (solid) freely movable on it. The threaded bushing rotates without forward movement on the threaded rod, since the maximum friction force in the thread (screw–solid) is much larger than the maximum air friction on the outer threaded bushing (solid–cylinder). If the bushing is fixed, the possible force for fixing the bushing (solid–cylinder) is considerably greater than the frictional force in the thread (solid–screw), and the bushing is moved forward at the maximum possible axial speed. Thus, at pure axial flow the maximum conveying capacity in a screw system is determined by the bulk density, the free cross-sectional area, the screw pitch, and the screw speed.
\[ \dot{M}_F = A_{\text{free}} \cdot T \cdot \rho_S \cdot n \]  \hspace{1cm} (1.2)

The conveying efficiency can now be determined at a given throughput, screw speed, and bulk density of the polymer as follows:

\[ \varphi = \frac{\dot{M}}{A_{\text{free}} \cdot T \cdot \rho_S \cdot n} \]  \hspace{1cm} (1.3)

and is between 0 and 1 [1].

In co-rotating twin-screw extruders, the deflection of the solid through the 8-shaped contour of the cylinder exerts a resistance and thus an increased circumferential force between the solid and the cylinder. This reduces the tendency for the solid to slip off the cylinder wall and results in an increased axial movement of the solid. Tests have shown that with the usual powder, fine grained, and granular granulate fillings the conveying efficiency varies only slightly with the given screw geometry. This can be traced back to the big influence of the suppression of rotation. As can be seen in Figure 1.1, the conveying efficiency decreases with increasing screw pitch. According to Equation (1.1), the optimum pitch in the feed zone is defined by the product of the intake pitch and the conveying efficiency. Therefore, Figure 1.1 also shows the effective intake pitch as the product of the intake pitch and the conveying efficiency [1].

![Figure 1.1 Conveying efficiency of co-rotating two- and three-lobed twin screw elements (effective intake pitch = conveying efficiency × intake pitch)](image)
A further parameter for the conveying behavior of the solids in the extruder is the conveying angle $\omega$. This is the angle between the circumferential direction and the actual conveying direction of the bulk material. The larger the conveying angle, the larger the solids transport in the extruder.

Figure 1.2 illustrates the conveying angle and the speed vectors using the example of a single-screw extruder.

If the screw was ideally smooth, i.e. the friction between the screw and the granules is much smaller than the friction between the barrel and the granules, the granules will move perpendicularly to the screw flanks (from A to C).

If the friction between screw and granules was much larger than the friction between cylinder and granules, the granules will adhere to the screw and move at a peripheral speed of $v_u$. The granule moves from A to B and stops without being conveyed ($\omega = 0^\circ$).

If the friction between the screw and granules was not significantly less than the friction between the cylinder and granules, the granules will move from A to A’.

If the granulate was completely prevented from turning with the screw, it will be transported from A to D (like a nut on a thread) [6].

Figure 1.2 Speed vectors and conveying angles in the solids conveying area of a single-screw extruder [6]

Vetter/Stark showed in their investigations [4] that with well-flowing, mostly granular, and low-compressible bulk materials with high feed limits, the throughput increases linearly with the screw speed (see Figure 1.3).

With these bulk materials, whose characteristic curve does not show any buckling, the feed limit only does not occur because the torque or plasticizing limit of the extruder is reached beforehand (e.g. PE2 max. 200 min$^{-1}$).

For bulk materials with unfavorable feed behavior, the throughput initially increases linearly at low screw speeds. Above a certain throughput, which depends on the bulk material properties, the throughput no longer increases proportionally
and a plateau is reached, i.e. the throughput no longer increases despite an increase in the speed. Vetter/Stark attribute the turning point to the effect of centrifugal forces, whereby the bulk material is pressed outwards, the frictional force at the housing is increased, and that at the screw is reduced, resulting in a larger conveying angle.

As the previous text shows, knowledge of material properties such as bulk density, flow ability, or particle size distribution for difficult bulk materials do not necessarily allow a clear conclusion to be drawn as to its feeding and conveying behavior. Although some work has already been done to describe the transport of solids in co-rotating twin-screw extruders (cf. e.g. [7–10]), to date no model is known which provides a satisfactory prediction, especially for powdery bulk materials. For this reason, tests are usually still required for such bulk materials.

For granular bulk materials, however, the simulation of solids transport in a co-rotating twin-screw extruder using the Discrete Element Method (DEM) is already very well possible, as the following results show. It is expected that the further development of the DEM models and an increase in computer performance will also make it possible to simulate powdery bulk materials in the future. The greatest difficulty, however, will remain the exact description of the material properties.
At Covestro (formerly Bayer Technology Services), the solids conveying behavior was investigated experimentally in a co-rotating, tightly intermeshing twin-screw extruder with 58 mm screw diameter and plexiglass housings, with movies being taken from above, below, and from both sides. The selected screw had an initial pitch of $1.4 \, D$ with subsequent pitch reduction to $0.7 \, D$. The investigated process conditions were simulated using DEM to determine the accuracy of the simulation. As can be seen from Figure 1.4 to Figure 1.7, experiment and simulation agree very well for all cases.

The different conveying angles of cylindrical and spherical granules are also reproduced very well, as Figure 1.8 shows.

Both experiment and simulation show that dosing fluctuations in the solids conveying zone cannot be compensated and, thus, have an effect at least up to the plasticizing zone (cf. Figure 1.9).

Due to the very good reproduction of reality, it is now possible to carry out screw design and process optimizations of the solids conveying zone of co-rotating twin-screw extruders for granular bulk materials by means of DEM simulation.

![Conveying direction](image)

**Figure 1.4** Comparison DEM simulation (top) with experiment (bottom) – top view
Figure 1.5 Comparison DEM simulation (top) with experiment (bottom) – view from below

Figure 1.6 Comparison DEM simulation (top) with experiment (bottom) – left screw

Figure 1.7 Comparison DEM simulation (top) with experiment (bottom) – right screw
1.1.2 Feed Limitations

Depending on the particle shape and melting behavior of the solids, different feed limitations result, which limit the overall throughput of the twin-screw extruder.

1.1.2.1 Granulates

Volumetric feed limitation by the maximum conveying capacity of the screws (see Equation (1.1)). Usually, however, the throughput with pellets is limited by the maximum available torque of the extruder (cf. explanations on Figure 1.3).
1.1.2.2 Powder

The feed limitation of powdery components depends on various material properties such as bulk density, compressibility, flow ability, and fluidizability. Essentially, powders are divided into free-flowing, fluidizable, and adherent or non-fluidizable powders [3].

The feed limitation of free-flowing and non-fluidizable powders is determined by the conveying capacity of the screws (see Equation (1.1)).

Fluidizable powders, on the other hand, can only be conveyed in the extruder up to their fluidization point (called “vortex point” in fluidized bed technology).

According to Vetter/Stark [4], feed problems occur in particular with fine-grained, cohesive, and compressible powders with the following bulk material properties:

- A low bulk density indicates a high air content of the bulk material.
- Fine-grained powders usually have high compressibility in the low-pressure range (0 to 100 mbar), i.e. in this range a lot of intermediate grain air is pressed off early during pressure build-up in the screw channel of the extruder in the solids conveying section.
- A high bed expansion behavior at the transition from fixed bed to fluidized bed leads to additional bulk density reduction in the feed area.
- Poor flow ability generally favors bridging in the feed zone of the extruder. This results in underfilling of the screws and pressure build-up cannot begin in this section.

If a bulk material has several of these properties, the throughput capacity of the extruder usually decreases [4].

The air drawn into the extruder inlet during dosing and the intermediate grain air pressed between the particles during compression and melting at the beginning of the plasticizing zone limit the feed of fluidizable powders. This air flows back into the screw channel in the opposite direction to the conveying direction of the bulk material and fluidizes it.

As investigations by Vetter/Stark [4] in a co-rotating twin-screw extruder with an unspecified cohesive plastic powder show, a strong decrease in the conveying angle is observed with increasing screw speed (see Figure 1.4). The reason was found to be the formation of air backflow, which completely fluidizes the bulk material in the screw channels.

With a screw pitch of 1.5 $D$, the conveying angle drops to almost 0° and then rises again slightly due to the centrifugal force. Due to the decreasing conveying angle, the throughput also increases only less than linearly with increasing speed.

With a screw pitch of 3 $D$, even negative conveying angles were observed above 200 min$^{-1}$. The bulk material is transported in the opposite direction to the conveying direction of the screws under the effect of the air backflow.
Nevertheless, mass flows (50 kg/h) were still conveyed at conveying angles of 0°, which can only be attributed to the conveying effect in the intermediate section of the screws. Here the bulk material is transported purely axially by transfer from one screw to the other by the width of the screw flank [4].

**Figure 1.10** Conveying angle $\omega_0$ as a function of screw speed $n_s$ and pitch $S$ for a co-rotating twin screw extruder [4]

Fluidization can be prevented or shifted to higher throughputs by:

1. Downstream open plasticizing zone, i.e. without backward conveying element at the end, through which the introduced air can escape without obstructing the powder flow.

2. Venting the screw channel in the solids conveying area by applying a vacuum. This increases the conveying angle [4]. Such a solution was implemented e.g. in the form of the Feed Enhancement Technology (FET) from Coperion [5].

3. Compaction of the fluidizable powder, which means that less air is drawn into the extruder. However, it should be kept in mind that compacting makes the dispersibility of the powder more difficult.

Powdery substances can change their properties during the dosing process so that their flow behavior is very difficult to determine and predict. This can be caused, for example, by the powder being enriched with air as it is fed into the extruder, thereby reducing its bulk density. This can be prevented or reduced by keeping the drop height from the dosing unit to the screws as low as possible and allowing air to escape well upstream and/or downstream in the extruder.
It can also happen that the bulk density of a powder in the lower area of a big bag is higher than in the upper area, or that in bags stored on a pallet at the bottom it is higher than in bags on top of the pallet. This can change the feeding behavior during the compounding process. Therefore, for powdery raw materials compaction during storage should be avoided.

1.1.2.3 Flakes
Especially thin flakes tend to jam in the gap between the screws and the housing as well as in the intermediate section of the screws, which can result in torque peaks that limit the throughput. In order to avoid jamming, the gaps in the feed area should be enlarged.

1.1.2.4 Low-Melting Components
Low-melting components, such as lubricants and release agents, can melt or fuse in the feed hopper if the temperature is too high. This usually leads to adhesion to the hopper wall, which strongly impedes or even stops the product transport into the extruder due to narrowing of the effective hopper cross-section or bridging. Therefore, the extruder intake barrel and possibly also the feed hopper should be cooled. Furthermore, low-melting substances can start melting or even melt completely in the solids conveying zone. If the composition of the formulation is unfavorable, this can lead to stick-slip effects, which in some cases result in such large torque fluctuations that a stable process is not possible or only at very low filling levels. This can be remedied, for example, by adding the low-melting components downstream into the melt or by more effective cooling of the solids conveying zone.

References for Section 1.1
1.2 Melting of Thermoplastics

In this section essential aspects of the melting of thermoplastics are illustrated. The tasks of the melting zone and the screw elements typically used in the melting zone and their configuration are only briefly discussed here; these topics are discussed in more detail in Sections 1.3 and 2.2 of the partner book *Co-Rotating Twin-Screw Extruders: Fundamentals*. The measurement methods used in the past to investigate the melting behavior are described in more detail. All the measurement methods provide a picture of the three main steps of melting. Finally, calculation models are presented with which the melting behavior in a twin-screw extruder can be predicted.

For all aspects relevant literature references are mentioned. Further literature overviews on the melting of thermoplastics can be found in the works of Bastian [1], Liu [2], and Moneke [3].

1.2.1 Tasks of the Melting Zone

In compounding, the polymer melting zone is often considered the most important process zone, as up to 80% of the energy required in the compounding process is used there. However, this energy-based explanation alone is not enough. At the end of the melting zone, the polymer melt should finally reach a consistency that enables optimum further processing in the subsequent process zones. During melting, the energy input primarily follows the enthalpy curve of the polymers, fillers, and additives used, so that high energy inputs are inevitable.

A good melting zone must fulfill further tasks beyond the energy input. The energy introduced should be distributed as homogeneously as possible in the melt. For example, Janssen [4] reports that despite very high speeds of up to 1200 rpm combined with very high energy input at the end of the melting zone there may still be unmelted pellets. Overall, the outlet temperature from the melting zone should be as low as possible in order to give the following zones more flexibility for further polymer processing. However, one should be aware that a lower melt temperature will lead to a higher viscosity and consequently to a faster heating of the polymer melt by viscous dissipation.

In addition to softening the polymers, the melting zone has the task of dispersing fillers and additives and already ensuring their uniform distribution as far as possible. Dispersion is particularly successful in the melting zone, where the lowest temperatures and thus the highest viscosities are present relative to the downstream process zones. This results in particularly high shear stresses on the fillers,
which lead to the fracture of the agglomerates. Andersen [5] proves with experimental results that an eccentric three-lobe kneading block should be used as the initial kneading element. In contrast to classic two-lobe kneading blocks, eccentric three-lobe kneading elements have narrower kneading discs, and two of the three tips have very large clearances to the barrel, which prevents or at least significantly reduces compacting of the fillers in the intermeshing region.

The performance of twin-screw extruders has increased further in recent years. With the top models, torque densities of up to 18 Nm/cm$^3$ are achieved at up to 1200 rpm. The throughputs made possible by this lead to ever shorter residence times in the extruders. Often the residence time after the melting zone is now too short to correct deficiencies in the melting zone. In order to avoid unmelted pellets, some extruders are only operated at a fraction of the maximum possible torque and thus at lower throughputs. This reduces the economic efficiency, as the possibilities of the extruder are not fully used. At high speeds and throughputs, the melting zone must be designed so that the polymer melt leaves the melting zone at an excess temperature. A large part of the polymer melt thus has a much higher temperature than actually required in order to keep the amount of unmelted granules within limits. The high speed alone also leads to very high shear rates in the screw clearances. Since the local energy dissipation is proportional to the square of the shear rate, very high temperature peaks occur in the clearance areas, which can lead to polymer degradation. Economic aspects also mean that compounding plants avoid time-consuming adjustments of the screw configuration to specific product types. Rather, one screw configuration must be used for melting unfilled, reinforced, flame-retardant, or easily flowing product types [4]. It is obvious that compromises have to be made in the melting process.

1.2.2 Screw Elements and Screw Configuration

Qian [6] conducted melting tests on a laboratory extruder with amorphous polyester with unheated barrels and a screw configuration consisting of conveying elements with a single active kneading block. Only at high throughputs and high speeds was a melt observed after several minutes of operation. In the laboratory extruder, the friction of the pellets with the barrel wall was sufficient in the long term to still achieve melting. Once a melt was present, complete melting could be maintained even at low throughputs and low speeds. The presence of an initial melt is therefore a prerequisite for fast and complete melting.

An initial melt can be forced by a pair of kneading elements. The kneading discs alone do not convey and with every quarter turn an approximately triangular volume forms in the intermeshing region between the active flanks of two two-lobe kneading discs and the barrel, in which some of the polymer granules are trapped.