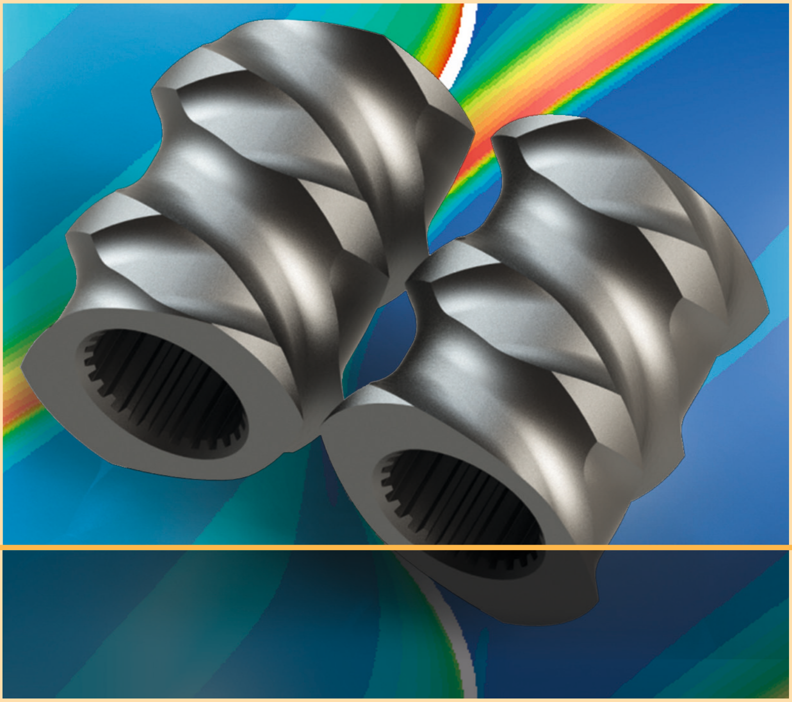
Klemens Kohlgrüber (Ed.)

Co-Rotating Twin-Screw Extruders: Fundamentals



HANSER

Kohlgrüber (Ed.)

Co-Rotating Twin-Screw Extruders: Fundamentals

Klemens Kohlgrüber (Ed.)

Co-Rotating Twin-Screw Extruders: Fundamentals

HANSER

Hanser Publishers, Munich

Hanser Publications, Cincinnati

The Editor:

Dr.-Ing. Klemens Kohlgrüber, Kürten, Germany

Distributed in the Americas by:
Hanser Publications
414 Walnut Street, Cincinnati, OH 45202 USA
Phone: (800) 950-8977
www.hanserpublications.com

Distributed in all other countries by:
Carl Hanser Verlag
Postfach 86 04 20, 81631 Munich, Germany
Fax: +49 (89) 98 48 09
www.hanser-fachbuch.de

Library of Congress Control Number: 2019949172

Editor: Dr. Mark Smith
Production Management: Jörg Strohbach
Coverconcept: Marc Müller-Bremer, www.rebranding.de, Munich
Coverdesign: Stephan Rönigk
Typesetting: Kösel Media GmbH, Krugzell
Printed and bound by Druckerei Hubert & Co GmbH und Co KG BuchPartner, Göttingen
Printed in Germany

ISBN: 978-1-56990-747-4
E-Book ISBN: 978-1-56990-748-1

Preface

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. This current English edition comprises about half of that greatly expanded German edition, with a focus on the basics of co-rotating twin-screw extruders. In particular, the following main points are described:

- Historical development.
- Process comprehension, especially compounding.
- Geometry of twin-screw screws and new patents for them.
- Material properties of polymers.
- Transport, pressure, and torque (power) behavior.

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. In particular, I would like to thank Dr. Smith from Carl Hanser Verlag, who managed this English edition and supported the publisher extraordinarily well!

Klemens Kohlgrüber, August 2019

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

The Authors

The Editor

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.

The Coauthors

Section	Author	
1.2	Martin Ullrich †	Formerly of Bayer Technology Services GmbH
1.3	Dr. Reiner Rudolf	Covestro Deutschland AG
1.5, 2.1	Dr. Thomas König	Covestro Deutschland AG
2.2	Dr. Ralf Kühn	Coperion GmbH
2.3, 4.7	Dr. Michael Bierdel	Covestro Deutschland AG
3.1, 3.4	Dr. Jens Hepperle	Bayer Crop Science AG
3.2	Dr. Jürgen Flecke	Covestro Deutschland AG
3.3	Dr. Heino Thiele	Formerly of BASF
3.5	Dr.-Ing. habil. Kalman Geiger	Formerly of the University of Stuttgart
3.5	Dr.-Ing. Gerhard Martin	Kunststoff Prozess Technik GmbH
4.5	Dr. Ulrich Liesenfelder	Covestro Deutschland AG
4.6	Dr. Carsten Conzen	Covestro Deutschland AG
4.6	Prof. Dr. Olaf Wünsch	University of Kassel

Order according to chapter structure.

Contents

1 Introduction

1.1 Technical and Economic Importance of Extruders

Klemens Kohlgrüber

1.1.1 Extruder Types and Terms

Screw machines are used for many process technology tasks. Normally the application takes place in continuous processes in which a screw machine can execute several process tasks simultaneously. It is a "multifunctional" machine. Although screw machines are able to do far more than extrude, mostly the term extruder is used. In the older German use of language also the terms "press" and "kneader" have been used. Corresponding to the old rubber screw presses, screw machines/extruders for plastics have initially been named plastic screw presses. This has been expressed for example by the title "Screw Presses for Plastics" of the first edition of the book of Gerhard Schenkel in 1959. The second edition of 1963 was renamed to "Plastic Extrusion Technology" [1]. Consistent with the current book title "Co-Rotating Twin-Screw Extruders" both terms, screws and extruders, have been "incorporated" into the book at hand.

Werner & Pfleiderer acquired licenses from Bayer for twin-shaft, exactly self-wiping, closely intermeshing co-rotating screw machines (see Section 1.2). They were named "ZSK", and this term was for a long time a synonym for this screw type. The term "ZSK" of Werner & Pfleiderer (today Coperion) is according to the former staff member and author Heinz Herrmann an abbreviation for *Zweiwellige Knetscheiben-schneckenpresse* ("twin-shaft screw compounder" in German; [2], p 179). Today the term is mostly shorted to "twin-(shaft)-screw kneader".

For this machine type many synonyms are in use, for example:

- Co-rotating twin screws (tightly intermeshing or non-intermeshing)
- Co-rotating extruder

- Co-rotating, closely intermeshing twin-shaft screw
- Co-rotating twin-screw extruder
- Co-rotating double-screw extruder
- Co-rotating twin-shaft extruder

The closely intermeshing twin-shaft screw with co-rotating shafts occupies a dominant position among the "extruders" and is applied in a variety of processes. An important application is found in the production, compounding, and processing of plastics. The co-rotating screws are also used in other industry sectors, e.g. the rubber and food industry.

1.1.2 Screw Machines and Plastics

The history of the plastics is very short, compared with the history of other materials (e.g., wood, metal, ceramic). The tremendous growth is very clearly illustrated in Figure 1.1.

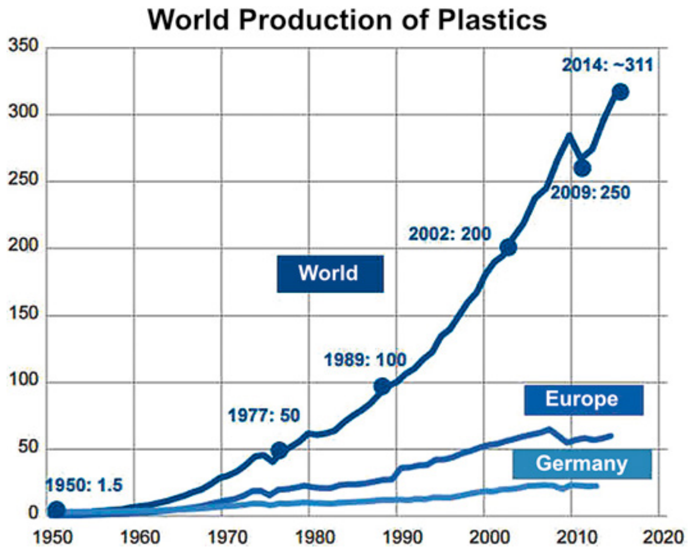


Figure 1.1 Diagram relating to the development of plastics worldwide during the last decades (ordinate: million tons) [Plastics Europe Deutschland e. V.]

What is the connection between the extruder and plastics production?

The success of the plastics industry is closely connected to the success of the extruders. Initially plastics were exclusively compounded discontinuously. This causes, however, economic limits at increasing production quantities. Furthermore, larger quality variations of the material were caused by discontinuous compounding (batch processing). Therefore, in the 1960s the continuous compounding process by means of extruders was developed. Meanwhile, nearly every plastic "passes through" an extruder during compounding and/or processing.

Figure 1.2 shows a typical plastic production comprising the reaction (or synthesis), compounding at the material producer and manufacturer of compounds, and processing to the semi-finished product or finished product.

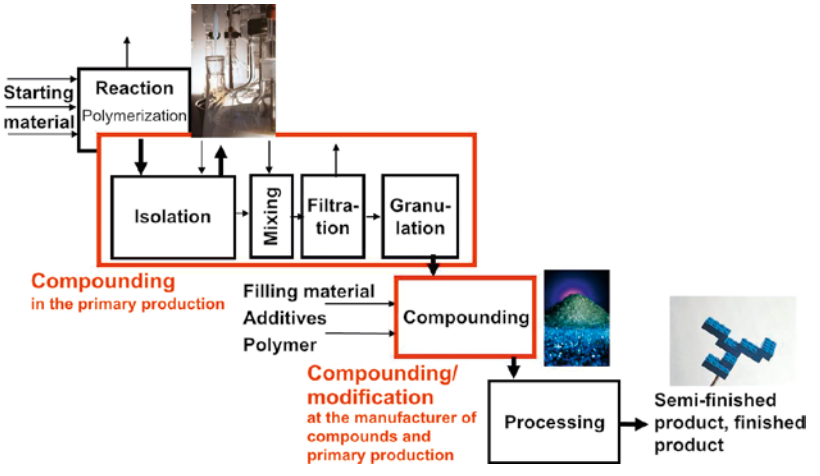


Figure 1.2 Plastic production with the compounding steps at the producer of raw materials and manufacturer of compounds

During compounding and processing of plastics the extruder plays a decisive role for melting, mixing, and dispersing. Therefore, two process steps shall be mentioned in the following section.

1.1.3 Economic Core Function of an Extruder in the Plastics Industry

1. **Melting of granulates or powders**
2. **Incorporation of additives or other polymers**

Why is the extruder a very important machine regarding the first point?

Plastics are usually treated in granular form (sometimes also as powder) between the polymer producer and the compounder, and between the compounder and processor. Only extruders are economically dominant for the continuous melting of granulate.

Why is the extruder a very important machine regarding the second point?

No polymer works without additives after the polymerization reaction. Normally, additives must be incorporated already at the raw material producer so that the polymer has a sufficient stability. In this context it is necessary to refer to the possible damage mechanisms (see Section 3.4). Furthermore, the polymers will be modified by additives. Only by this will they become ready for use and better able to be processed. The compounder also generates many new products with "tailor-made properties" by the addition of additives and production of blends. History has shown that new plastics mainly originate in this way, not by the development of new basis polymers. Conclusion: extruders are used very successfully for the compounding of existing products and development of new products. The following Figure 1.3 of Coperion GmbH gives an impression of the sold quantities of compounding machines.

Polyolefins	814
Technical plastics	4,350
Masterbatch	1,160
Long-fiber reinforced plastics	36
Temperature and shear sensitive plastics (PVC, cables, TPE)	1,659
Powder coatings, toner	602
Direct extrusion/calender	160
Chemistry and reaction technology	543
Food extrusion	270
Others	766
In total	**10,360**

More than 25% of all installed compounder systems worldwide come from Coperion.

Figure 1.3 Importance of compounding extruders [Coperion GmbH]

KraussMaffei Berstorff GmbH has also built "several thousand twin-screw extruders" as per information on the occasion of the Chinaplast trade show in April 2016.

The core function, the incorporation of additives, requires the extruder to have good mixing and dispersing abilities. This is one of the strengths of the co-rotating twin-screw extruder. In the range of the product discharge, a pressure build-up is required and normally the product must be cooled via the housing walls. The extruder type can perform these functions only with low effectivity. This is due to the poor pump effectiveness (Chapter 4) and the restricted cooling ability of heavy machines.

Compounding is described in detail in Section 1.3. Besides the description of the functional zones and process variables, practical information regarding the layout of the compounding machines are given.

1.1.4 Extruder Types and Advantages of Closely Intermeshing Co-Rotating Screws

There are several types of screw machines or extruders, which can be classified according to their number of shafts (Figure 1.4).

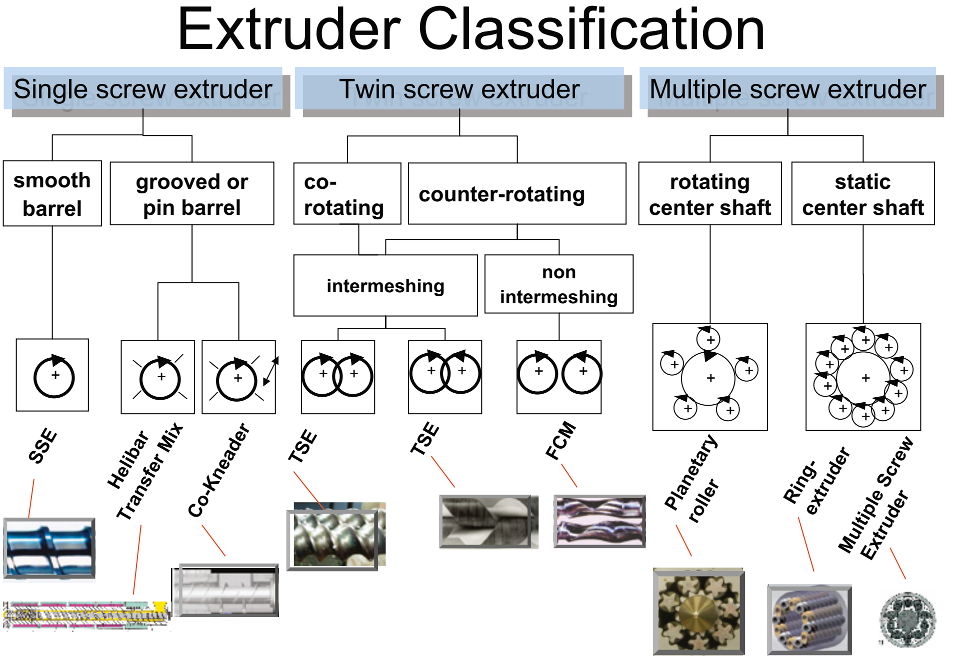


Figure 1.4 Classification of screw machines/extruders by the number of shafts

Single-shaft (single-screw) machines with a smooth-bore housing (barrel) as well as those with grooves and/or pins in the housing are utilized in plastic processing primarily for melting and pressure build-up. As the mixing ability of single-screw extruders is limited, co-rotating twin-screws (with two shafts) are often used for compounding tasks. This advantage is mentioned above as a core function.

For special applications a conical co-rotating execution has been developed. Furthermore, there are multi-shaft extruders, which partly have the geometry of two-shaft extruders, for example the ring extruder of the company Extricom. Multi-shaft extruders are presented and compared in detail elsewhere [3].

Co-rotating twin-screws are built using a modular design and can thus be adapted easily to handle a variety of processing requirements and product characteristics. A further essential advantage of the closely intermeshing co-rotating screw is – in contrast to the single-shaft machines – that the flights mesh tightly except for the necessary clearance. The screws, and thus the machine, are designated as kinematically “self-cleaning”. Compared to a normal single-screw machine, where the flights scrape the inside of the housing (while maintaining a certain clearance between the screw and housing), the flights in a closely intermeshing twin-screw arrangement also clean each other. Conceptually, the twin-screw arrangement can thus be understood as a primary screw and a “cleaning screw”.

On the market, there are very small laboratory extruders for product developments with small throughputs of $x \cdot 10$ g/h up to production extruders with $x \cdot 10$ t/h (factor $x < 10$). Because of the small product requirement, the smaller machines are especially suitable for development tasks with very expensive materials.

1.1.5 First Closely Intermeshing Co-Rotating Screws

The first closely intermeshing co-rotating screws were built by Bayer using their own design and featured a vertical arrangement of screws. Figure 1.5 and Figure 1.6 show such a screw arrangement built by Bayer for chemical reactions.

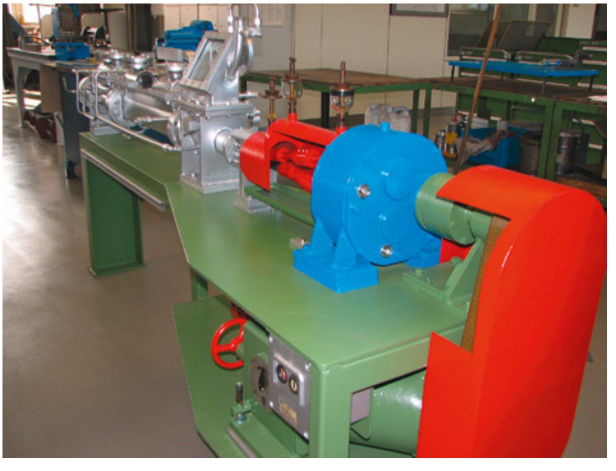


Figure 1.5
Historical chemical laboratory screw from Bayer with vertical arrangement of screws

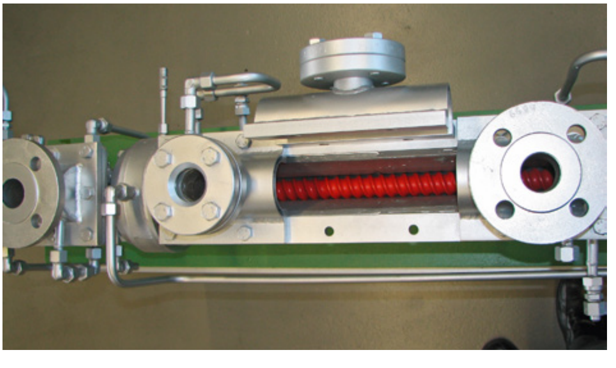


Figure 1.6
Screw shown in Figure 1.5, view from above

The screw shown in Figure 1.5 and Figure 1.6 has been restored by Coperion and can be visited there.

As a laboratory and trial machine, the machine shown in Figure 1.5 and Figure 1.6 has no casing to provide easy access and be readily convertible. In contrast, the first machines of the company formerly called Werner & Pfleiderer (today Coperion) were nearly fully encased in “the fashion of the day”; see Figure 1.7, which shows two ZSK machines from the 1950s. The first co-rotating screw type ZSK went into operation in 1957. Also, Werner & Pfleiderer initially built machines with vertical screw arrangement, as the sectional drawing in Figure 1.8 shows. The figure also shows that the actual processing section is very small in relation to the drive unit. At that time, the machine brochure promoted the “oversized drive” (with reliable operation as the benefit).

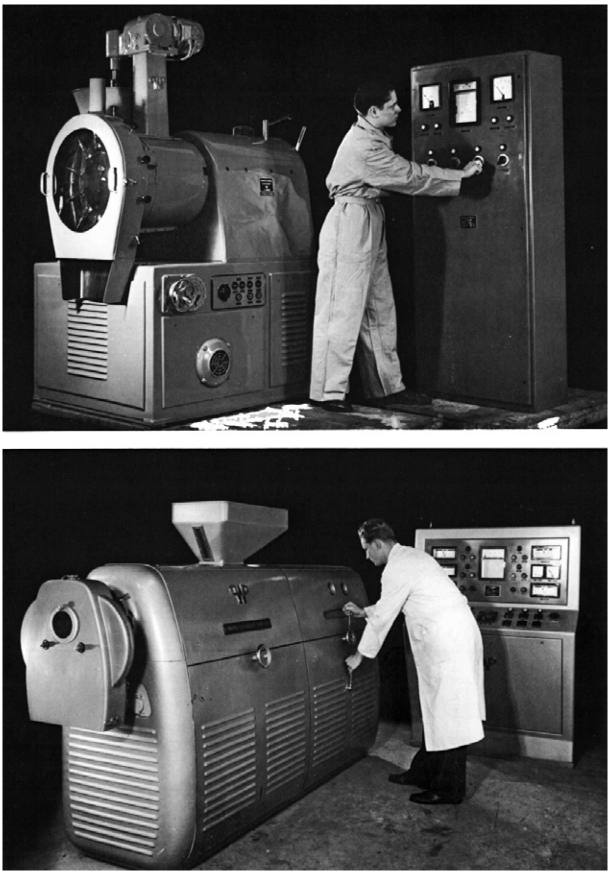


Figure 1.7 Werner & Pfleiderer’s ZSK machine from the 1950s. Original figure caption: “In the 1950s WP, together with major chemical companies, made a significant contribution to the burgeoning age of plastics. The top figure shows a plasticizing unit for producing flexible PVC, the bottom figure the first twin-screw extruder for compounding plastic pallets”

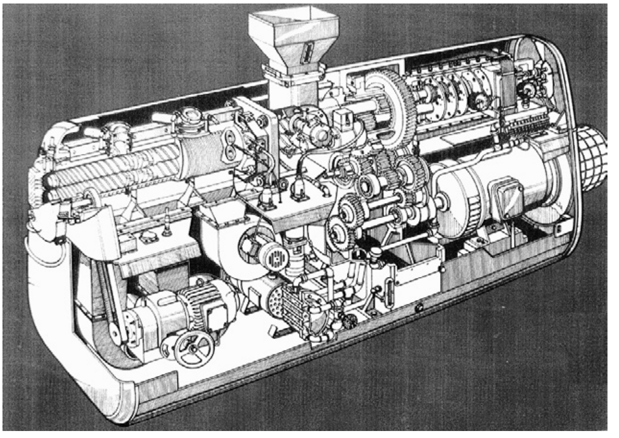


Figure 1.8 Section through a historic ZSK (Coperion GmbH)

In fact, the available torques were high for machines built then, but over the course of time it was possible to increase them even further. As the following sections will show, besides the torque also the speeds could be increased considerably.

1.1.6 Details of Twin-Screws

Section 1.2 presents a detailed summary of additional historical developments of co-rotating twin-screw extruders. Here, the modular approach to screw configuration will be specifically detailed. The shaft with screw flights is no longer manufactured "in one piece", but rather consists of a core shaft with slipped-on screw elements and kneading elements. Section 2.2 provides an overview of the many screw elements used and their principle of operation. An extensive survey of patents relating to screw elements and screw geometries can be found in Section 2.3.

Section 2.1 presents a very detailed description of how to create the basic geometries for conveying and kneading elements. For closely intermeshing profiles, the geometric cross-section of these screw elements depends on only three characteristics: the number of flights, the diameter, and the distance between shaft centers (Section 2.1.2). Conveying occurs at the screw profile with a pitch. Together with the necessary clearances, six specifications are sufficient for the determination of the basic geometry: number of flights, diameter of housing, distance between the shaft centers, the flight pitch, the clearance between the screws themselves, and the clearance between the screw and housing. For the clearance between the screws themselves a "clearance strategy" must still be fixed (Section 1.2.2.4.2). The so-called longitudinal cut equidistance represents a good compromise.

1.1.7 Objective of the Book

For the optimal design of a co-rotating screw for adaption to the task and product, a comprehensive knowledge of the machine (what can the machine perform?) and process (how does the product behave in the machine?) is required. Besides the specific knowledge in the areas product, process technology, and mechanical engineering, especially the knowledge of the interplay of the areas is necessary (Figure 1.9). Just this necessary basic knowledge is what this book conveys. It can be used for screw design and scale-up/-down.

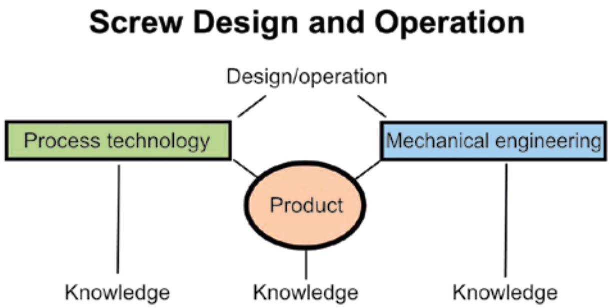


Figure 1.9 Necessary basic knowledge of the individual areas and their interaction

In Figure 1.9 the term product has been chosen for the material to be processed in the extruder. This term needs further clarification, because for machine builders "their product" is of course the machine. The term in Figure 1.9 stands as a synonym for material, pellets, granulate, polymer, food, extrudate, blend, etc.

In accordance with the three states of matter, the "material" in the extruder can be solid, liquid, and gaseous. For instance, in the melting area of a compounding extruder there is solid granulate, melted granulate as highly viscous liquid, and maybe drawn-in air or auxiliary gases from the feed section. Gaseous materials occur also when removing volatile components, e.g. solvents and monomers. Solid materials (granulate, powder, etc.) are dosed and can occur also as extrudate, e.g. at crystallization in special crystallization screws. Very highly viscous materials with simultaneously low-viscous water are utilized in so-called (single-shaft) **dewatering extruders** in the rubber industry. For most applications of the screw machines, however, the process zones, also named functional areas, are supplied with highly viscous liquids and blends. These applications are the main focus of this book.

1.1.8 Summary

The co-rotating twin-screw extruder is, due to its mode of operation and modular design, a multifunctional machine. Its success in terms of the number of units was and is closely connected with the economic success of plastics. The economic core function of extruders in the plastics industry is:

- Melting of granulates or powders

and additionally of co-rotating twin-screw extruders:

- Incorporation of additives or other polymers.

The disadvantages of a poor pump efficiency to the pressure build-up and the restricted product cooling effectivity in large extruders, both relevant especially in the range of the product outlet at the end of the extruder, are accepted.

1.1.9 Prospects

A forecast of the author regarding further developments and applications:

- Further development of new self-cleaning screw geometries differing from the basic "Erdmenger" profile
- Incremental increases of the "usual further developments": maximal length of screw L/D, product volume (expressed by D_a/D_i), and torque M_d/A^3 (A = center distance)
- Increased applications in the food and pharmaceutical industries
- Sporadic additional applications in the primary plastic production for reactions in mass without solvents (at short reaction times)

References for Section 1.1

[1] Schenkel, G., *Kunststoff-Extrusionstechnik*, Hanser (1963)

[2] Herrmann, H., *Schneckenmaschinen in der Verfahrenstechnik*, Springer, Berlin, Heidelberg, New York (1972)

[3] Kohlgrüber, K., Zwei- und Mehrwellenextruder, annual VDI-Forum with speakers from machine manufacturers and the chemical industry *(https://www.vdi-wissensforum.de/weiterbildung-kunststoff/zwei-und-mehrwellenextruder/)*

■ 1.2 Historical Development of Co-Rotating Twin-Screw Extruders

Martin Ullrich

1.2.1 Preface and Recognition of Bayer Scientists

Klemens Kohlgrüber

Since the publication of the first edition the author of the section "Historical Development of Co-Rotating Twin-Screw Extruders", Mr. Martin Ullrich, sadly passed away. Also Mr. Juri Pawlowski, who provided fundamental identification numbers and interrelations through his works on similitude theory of extruders, died at the end of 2013. In memory and as recognition of the work of these scientists I therefore would like to add some remarks.

In Section 1.2.2.1, Ullrich briefly goes into the matter concerning the Bayer developments for the "co-rotating screw system". Professor J. L. White, who died in 2009, describes in his book *Twin Screw Extrusion* quite extensively the research from Bayer (formerly IG Farben) in this area. This is expressed by some sub-chapter titles from [1] (selection):

- The Meskat-Erdmenger-Geberg, L. G. Farbenindustrie Wolfen Works Twin Screw Development Program
- Meskat Bayer (Dormagen) Program
- Erdmenger Bayer (Leverkusen) Program
- The Werner-Pfleiderer ZSK System Erdmenger
- Later Bayer Developments

As a complement, reference is made to the "timetable of the history of development of screw machines" ([2], pp. 38–47).

The basic patent of the threaded screw comes from Meskat and Erdmenger and dates back to 1944 (Section 1.2.2.1.2). Meskat later became mayor of Dormagen, and Erdmenger managed the "Screw Group" at Bayer in Leverkusen until 1976. Then Ullrich took over this group, which he later renamed "High-Viscosity Technology". After Ullrich's retirement in 2000, I became head of the group and was able to expand the group, in both staff and thematic, and renamed it to "High-Viscous, Mixing and Reactor Technology".

The tightly meshing self-cleaning geometries for co-rotating screws as per the former patents are often called "Erdmenger Geometries". This reflects also the above sub-chapter title of [1] ZSK System Erdmenger. A recognition for Erdmenger is given in Section 1.2.2.2.4. Here, I would like to refer briefly to the works of Pawlowski and Ullrich.

Juri Pawlowski made many valuable contributions, especially in his theoretical works at Bayer concerning the similitude theory in physical-technical research, on which he wrote a book [3]. A valuable development was the derivation of dimensionless process factors and dimensionless conveying parameters (profile parameter $A_1, \ldots$) for single-shaft screws [3]. The conveying parameters of the single-shaft screw were measured then. Later, we calculated these very exactly and were surprised at the extremely good measured values [4]. On another topic, the representative shear rate, Mr. Pawlowski sent me an e-mail on January 12, 2013 (when he was 93 years old):

> *"The application of the representative shear rate results i. a. in an unfounded and an inadmissible similarity theory of reduction of the pi-area which is required by a chemical engineering process. But there are some more simple problems of the creeping flow at which the 3rd invariant of the deformation speed tensor div(v) is equal to zero (e. g., parallel plate-, tube-, and Couette flow) and the representative values (viscosity, shear rate, shear stress) act as mathematically exact solutions.*
>
> *And still another incidental remark: Several authors are seeking to approximate the flow curves of non-Newtonian materials mathematically. But this is of little use with regard to the similarity theory: 1. There are legions of rheological material equations of different mathematical structure and 2. The methods based on the similarity theory apply likewise to all flow curves, regardless of their possible approximation."*

In his book, Pawlowski shows that in non-Newtonian materials "without memory" only two dimensionless process factors of the extruder arise and the other material parameters arise isolated dimensionless, for example at creeping flow (Equation 6.3.2 in [3]).

$$\Delta p^{*} = f_{\Delta p}\left(\dot{V}^{*}, n \cdot \theta, \frac{L}{D}, \pi_{rheological,i}\right) \tag{1.1}$$

Here, the dimensionless process factors comprising two dimensioned properties are pressure and extruder speed. θ is a time constant in the rheological description and $\pi_{\text{rheological,i}}$ are dimensionless material constants which do not depend on process parameters. With the Carreau approach for viscosity (Section 3.1), often used in this book, the dimensionless pressure can be formed with the zero viscosity. The product of speed and rheological time constants is also named Deborah number. $\pi_{\text{rheological}}$ is then the flow exponent. Detailed information regarding Equation (1.1) will follow in Section 1.4.

Pawlowski worked mostly on a theoretical basis and also published his results, whereas Ullrich worked very closely with polymer production companies and documented his developments in the field of the co-rotating screw system mainly in internal Bayer reports. The following Figure 1.10 shows a summary of a report of 1973. Hence follows:

- The “dimensionless description according to the theory of similarity” of the conveying, pressure, and capacity characteristic for single-shaft extruders introduced by Pawlowski has been applied by Ullrich to twin-screw extruders.
- The linear dependence of dimensionless process key figures for single-shaft screws theoretically proven by Pawlowski has been shown by Ullrich experimentally for twin-screw extruders.
- The conveying parameters (= profile parameters) A_1, A_2, B_1, and B_2 have been determined using a newly developed measurement equipment via the axis intercept equation.
- In this report several screw pitches have been analyzed and further examinations with varied screw clearance, kneading discs, and partly filled screws have been announced.

Das Förderverhalten gleichsinnig rotierender, kämmender Doppelschnecken bei Newtonschen Flüssigkeiten

Zusammenfassung

Das Förderverhalten von Schneckenmaschinen bei Newtonschen Flüssigkeiten hat einen Druckaufbau- und einen Leistungsaspekt und kann nach Dr.Pawlowski mit 3 dimensionslosen Kennzahlen in 2 linearen Zusammenhängen vollständig dargestellt werden. Ein beliebiges Schneckenprofil wird in dieser Darstellung durch 4 experimentell zu ermittelnde Parameter gekennzeichnet.

In Versuchen mit einer zweiwelligen, kämmenden Meßschnecke (Schneckentyp der ZSK-Serie) wurde die Eignung dieser Betrachtungsweise auch für mehrwellige Schnecken nachgewiesen (s. Abb. 2-9). Weiterhin wurden die wichtigen Profilparameter für verschiedene Schneckensteigungen bestimmt, so daß die fördertechnischen Aspekte von ZSK-Schnecken jetzt auch ohne Experimente berechnet werden können (s. Beispiel Pkt. 7).

Weitere Untersuchungen über das Förderverhalten von teilgefüllten Schnecken, Knetscheiben und Schnecken mit variiertem Spiel sollen sich anschließen.

Figure 1.10 Extract from a report of Martin Ullrich dated September 20, 1973 [5]. English translation below

The Conveying Characteristic of Co-Rotating, Intermeshing Twin-Screws at Newtonian Liquids

Summary

The conveying characteristic of screw machines at Newtonian liquids has a pressure build-up and a capacity aspect and can as per Dr. Pawlowski depicted totally with 3 dimensionless key figures in 2 linear interrelationships. An arbitrary screw profile will be marked in this representation by 4 parameters to be identified experimentally.

During tests with a two-shaft, intermeshing measuring extruders (screw type of the ZSK series), the suitability of this approach has been proven also for multi-shaft screws (see Fig. 2-9). Furthermore, the important profile parameters for different screw pitches have been determined, so that the conveying aspects of ZSK screws can be calculated now without experiments (see example point 7).

Further tests relating to the conveying characteristic of partly filled screws, kneading discs and screws with varied clearance shall follow.

The tests announced in the last point were also executed with the newly developed experimental apparatus (Figure 1.11). Using a two-sided bearing of the screw shafts and a floating bearing of the drive, the torques can be measured very exactly by means of a spring balance. The housings are partly made of Plexiglas and as model liquid mostly high-viscous transparent silicone oil was used. This allows experiments at room temperature. By means of temperature measurements a product heating by liquid friction (dissipation) was determined and taken into account in the evaluation (viscosity reduction). All sensors were "mechanical" and did not have electronic components, which were not available at that time. Today the equipment is still operational and is used occasionally.

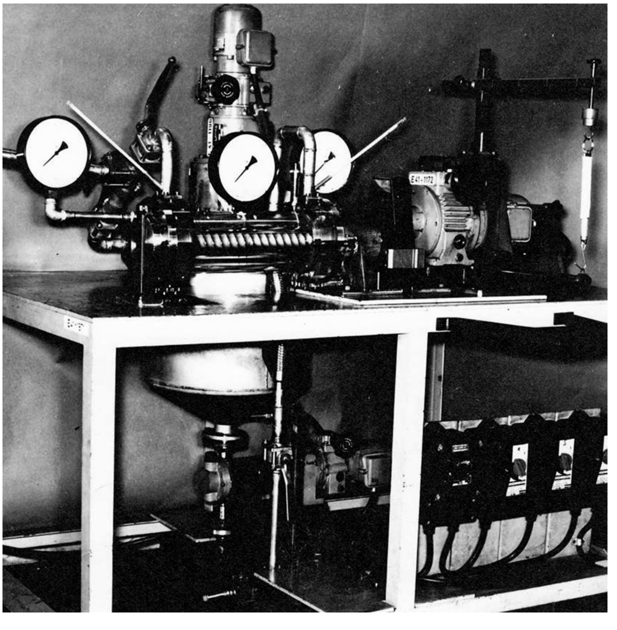


Figure 1.11
Experiment apparatus for determination of the conveying characteristic of twin-screws

For decades a staff member of Mr. Ullrich executed measurements with this measuring screw. The linear relations between dimensionless pressure and dimensionless capacity in dependence of the dimensionless throughput pointed out theoretically by Pawlowski have been confirmed also for twin-screw extruders by Ullrich based on numerous measurements. The linear dependence for Newtonian materials has been very generally proven by Böhme for creeping flows [6].

From the numerous results [7], the reciprocal values of the maximal achievable pump efficiency for some extruder geometries are depicted as an example in Figure 1.40. The related terms can be found in Figure 1.42.

In the area of polycarbonate primary production Ullrich introduced a “key technology” with the co-rotating screws. There existed a division of work with Dieter Löhr. Ullrich developed the production screws for the polycarbonate primary production (also polycarbonate manufacturing) and Löhr was, as head of the compounding technical center, responsible for the compounding. A description of the contemporary Bayer compounded products and basics thereof was provided by Löhr in the *Kunststoffhandbuch* (Handbook of Plastics) [8].

Due to the collaboration of Ullrich with the polymer production, people from production did not want to publish further developments in the field of co-rotating screws. The collaboration with the extruder manufacturer Werner & Pfleiderer (Bayer licensee) was effected in great secrecy. Internally, the works of Ullrich were very much appreciated and thus, a company-wide Bayer award, the Otto-Bayer-Medal, was presented to Ullrich in 1988, as for the scientist Pawlowski three years earlier. In my later farewell speech on the retirement of Mr. Ullrich, I honored symbolically the “screw developers” Erdmenger, Pawlowski, and Ullrich (Figure 1.12) and named a relation for co-rotating screws, which is not presented in this book, after Ullrich [9].

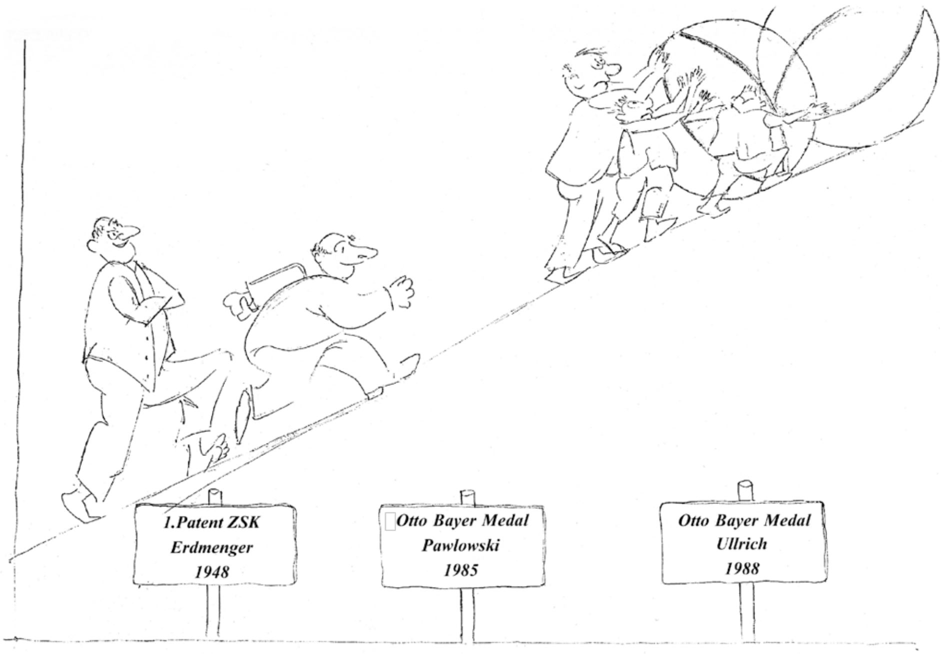


Figure 1.12 “Advancement” of the Bayer screw developers [8]

Ullrich has recorded his innovations, besides in the internal Bayer reports, in 47 patents. Thereby, the accomplishments of Mr. Ullrich became known beyond Bayer, and Werner & Pfleiderer proposed and arranged for the honoring of Mr. Ullrich with the "Heinz Herrmann Award" (Figure 1.13). This award should have been presented him on the occasion of the ANTEC conference in the USA in 2010. However, because of his ill health, Mr. Ullrich was no longer able to travel, although he had prepared an acceptance speech. From this:

"At the end of my speech I would like to thank the SOCIETY OF PLASTIC ENGINEERS for the outstanding honor you gave me with the bestowal of the HEINZ HERRMANN TWIN-SCREW EXTRUSION AWARD. This special recognition is one of the greatest delights of my professional life."


Society of Plastics Engineers
ANTEC 2010
In acceptance of the
Heinz Hermann Twin-Screw Extrusion Award
to the late Mr. Martin Ullrich

Figure 1.13 Award for Martin Ulrich

Regrettably, he died before the date of the award ceremony. Together with an American co-worker, Mr. Vitkovski, I transmitted as a "thank you" a video message that was presented at the ANTEC.

At the retirement celebration for Ullrich from Bayer in 2000 I honored the three Bayer screw scientists Erdmenger, Pawlowski, and Ullrich by the following Figure 1.14. Mr. Erdmenger was already dead then. Mr. Pawlowski was very pleased about this drawing on January 3, 2013.

Figure 1.14 "Screw developers": Erdmenger, Pawlowski, and Ullrich [8]

At this point I would like to thank Mr. and Mrs. Löhr for creating Figure 1.12 and Figure 1.14 for that occasion [9]!

References for Section 1.2.1

[1] White, L.J., Kim, E.K., *Twin Screw Extrusion,* 2nd ed., Hanser (2010)

[2] Herrmann, H., *Schneckenmaschinen in der Verfahrenstechnik,* Springer (1972)

[3] Pawlowski, J., *Die Ähnlichkeitstheorie in der physikalisch-technischen Forschung,* Springer, (1971)

[4] Beck, D., Kohlgrüber, K., Berechnung der Wärmeübertragung in Schneckenmaschinen, CIT 66 (1994), No. 8, pp. 1073–1076

[5] Ullrich, M., Das Förderverhalten gleichsinnig rotierender, kämmender Doppelschnecken bei newtonschen Flüssigkeiten, internal report, Bayer, September 20, 1973

[6] Böhme, G., Theoretische Betrachtungen über schleichende Strömungen. In Festschrift, Universität-GH Essen (1995), pp. 27–40

[7] Ullrich, M., Das Förderverhalten von Doppelschnecken, internal report, Bayer, February 9, 1989

[8] Löhr, D., Herstellen von Compounds, in: *Kunststoffhandbuch,* Becker, G.W., Braun, D., Eds, Vol. 3/4, pp. 299–314

[9] Kohlgrüber, K., booklet on the speech at the retirement from Bayer of Martin Ullrich, October 26, 2000

1.2.2 Historical Development of Co-Rotating Twin-Screw Extruders

Martin Ullrich

This section covers the engineering-related history of the twin-screw, or more precisely the co-rotating twin-screw extruder, where both screw shafts rotate in the same direction. In the following, we will simply refer to them as co-rotating extruders (instead of co-rotating twin-screw extruders).

The best place to start with is a brief account of the origin of all multiple screws, namely the single-screw extruder. Its inventor, Archimedes [1] (approximately 2250 years ago), used it to transport water overcoming differences in elevation. The same principle is still used today in Egypt, Holland, and in many water purification plants.

1.2.2.1 Early Developments

The single screw as an "extrusion apparatus" was developed in the second half of the 19th century and was used intensively in industrial and heavy engineering applications. It was used in three major industries:

- Pottery industry: ceramic compounds
  - extrusion, shaping
- Rubber industry: natural rubber, gum
  - plastification, extrusion,
  - profile production

- Food industry: oily fruits, oil seeds
  - extracting biological oils,
  - separation of material using “strainer screws”,
  - meat processing by meat grinder

Product feed in a single screw initially appears somewhat strange. While every metal molecule remains in the same cross-sectional plane, the product is nevertheless conveyed axially. Following is an attempt at an explanation: when considering the screw and the product, the screw rotates without changing position, although the product does not rotate but slides axially, in other words, it is axially conveyed. This so-called “theoretical” conveying does not exist in practice, however, because the product is not a solid body but a highly viscous fluid with a rheological character.

The adhesion and friction characteristics of the plastic material determine the intensity of the flow. In the case of Newtonian fluids this is half of the theoretical conveying (at constant pressure) and even less with counterpressure (extrusion), even down to zero. In the latter case, the product rotates with the shaft and throughput ceases.

This weakness of the single screw, particularly the fact that there is no cleaning of the shaft and the strong dependence of conveying on rheological properties, motivated inventors to seek solutions to these problems. The co-rotating extruder was therefore initially proposed as a self-cleaning mechanism. Six patent citations [2–7] over a 70-year period (1869–1939) show that the co-rotating extruder remained very much at the forefront of engineers’ minds. J.L. White [44] provides an extensive, thorough description of the developments and patent situation in this field.

In the early 1940s, a systematic investigation into the co-rotating extruder system began at the IG plant in Wolfen, Saxony-Anhalt. It involved the combined physical, mathematical, engineering, and mechanical expertise of a team composed of W. Meskat, A. Geberg, R. Erdmenger, and their staff. The team was commissioned to develop a reliable “mechanical apparatus” for chemical processes with highly viscous products.

The work was continued at Bayer AG in Leverkusen with strongly process-orientated groups [8] under the new “applied physics” (AP) organizational structure introduced by K. Riess and implemented by K. Sigwart in 1948. R. Erdmenger founded and led one of these engineering groups, which was composed of 10 to 15 specialists and employees, until 1976. The group was later given the name “High Viscosity Technology”.

This team, as part of the chemical industry, was of course primarily involved with solving problems in the area of high-viscosity engineering, particularly in developing chemical processes for the Bayer AG. The mechanical aspect was developed as required and to varying degrees of intensity.

With respect to screw geometry, we turn back the clock to Wolfen, where the team was searching for the perfect mechanical apparatus for high-viscosity technology. It had to function despite the adhesive, frictional, and antifrictional properties of the product, cope with various material consistencies, and overcome rheological changes caused, for instance, by reactions in the machine.

The desired self-cleaning function led to the development of the intermeshing twin screw. The counter-rotating screw was discarded, because it tended to get blocked by solids and was a poor mixer; attention focused instead on the intermeshing, co-rotating extruder.

1.2.2.1.1 Basic Geometry

A. Geberg addressed the geometric kinematic problem with a mathematical equivalent view. He discovered the fact that the co-rotation of two shafts around their fixed axes is the kinematic equivalent of the "movement without rotation" of one shaft around another fixed shaft (Figure 1.15). In the case of this so-called "movement without rotation", which happens when the profiles are touching, all mass points of the moved screw move in circles with radii equivalent to the centerline distance (Figure 1.15).

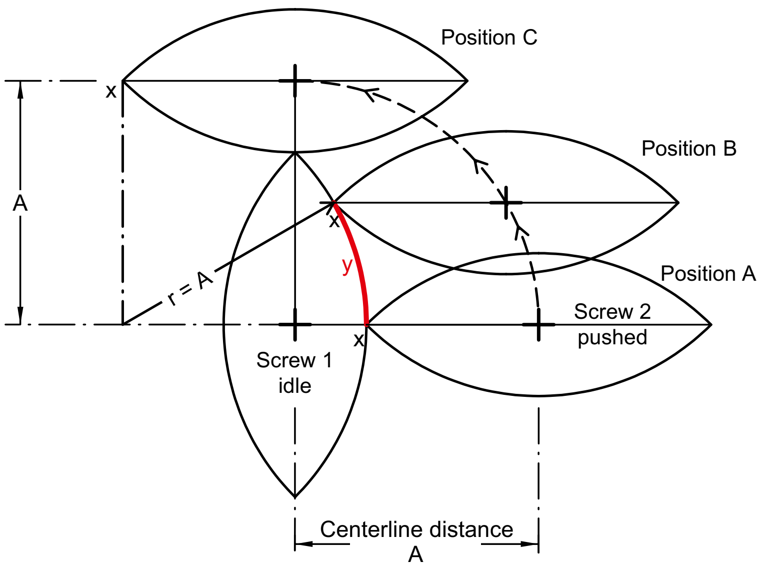


Figure 1.15 Kinematic equivalent view "movement without rotation" (screw with tip width 0)

Because the – mathematically precise – system is intended to be fully wiping, the central shaft can be a wax blank that is shaped to its corresponding contour by the metal moved screw. The moved screw (Figure 1.15) with its metal tip *x* then forms the flank arc *y* (bold) in the fixed wax shaft. As all mass points of the moved screw describe circles with a radius equal to the centerline distance, including the tip *x*, the flank arc *y* of the wax screw must also be an arc with a radius equal to the centerline distance of the two screw shafts: an astonishingly simple solution.

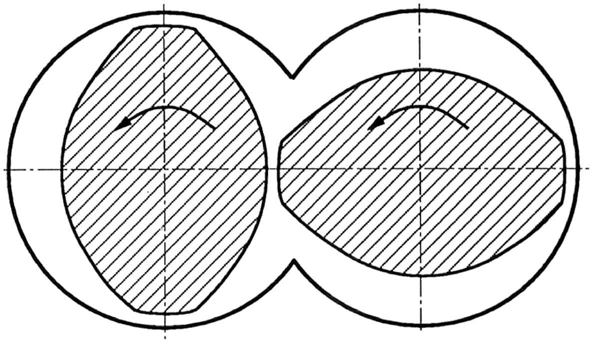


Figure 1.16 Screw with tip width, cross-section

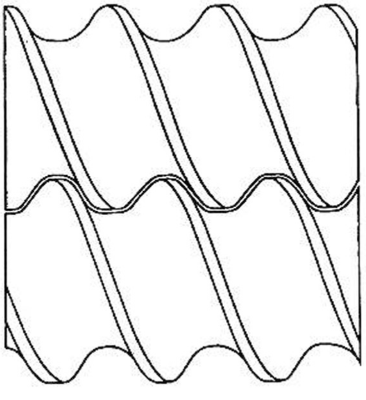


Figure 1.17
Axial view of screw

Real screws do not have points in position *x*. They have specific tip widths (Figure 1.16), which have previously been omitted to clarify the kinematics (Figure 1.15). It helps here to determine the kinematics in cross-section, then to advance the resulting cross-section profiles axially, and finally to apply a twist to obtain the longitudinal section contour and the desired three-dimensional screw (Figure 1.17).

A. Geberg supplemented his investigations by determining the basic geometries of screws in practical applications with varied parameters: number of threads and channel depth and their dependent variables, tip angle (Figure 1.18), and free cross-sectional area that can be filled with product (Figure 1.19).

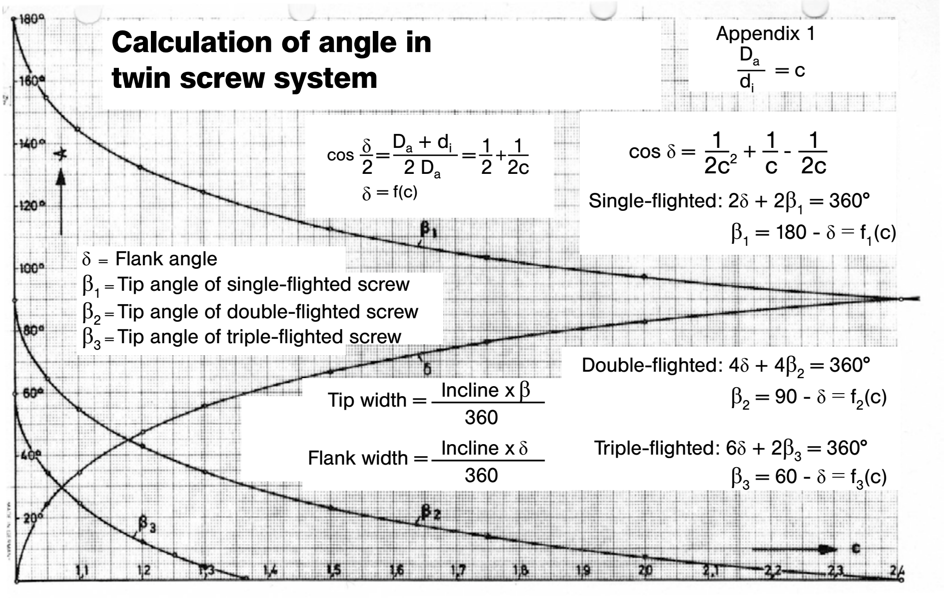


Figure 1.18 Characteristic angle diagram [11]

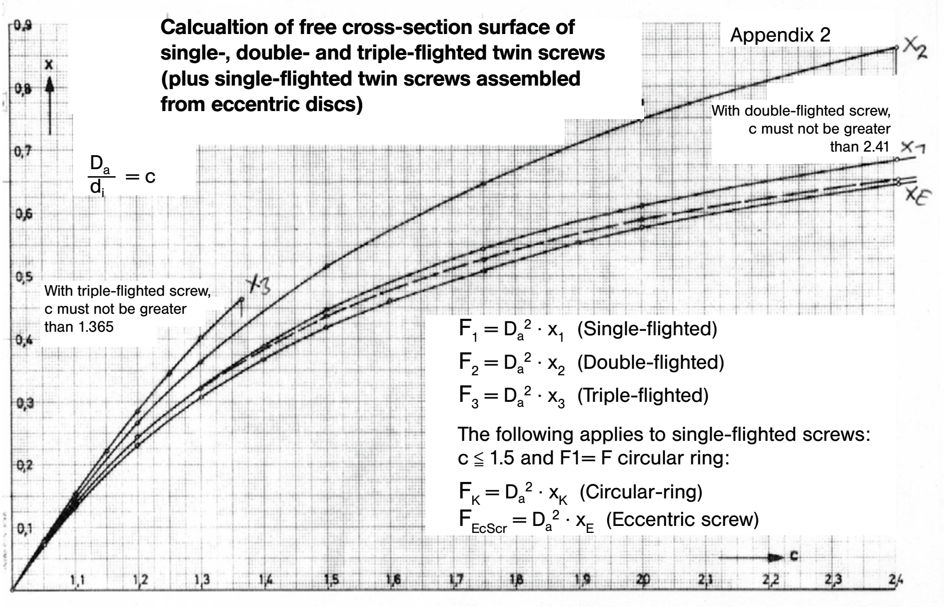


Figure 1.19 Characteristic cross-section area diagram [11]

In 1978, during his retirement, R. Erdmenger published a paper [9] looking back over his career and the significant role he played in the development of the co-rotating extruder. In this paper he cites the work of W. Meskat, A. Geberg, and R. Erdmenger (1944) on the basic geometry in Wolfen [10], extracts from R. Erdmenger and S. Neidhardt (1948) in Leverkusen [11], and his own tests on laboratory screws in Leverkusen in 1948/51 [12].

1.2.2.1.2 Basic Patents

The bibliography includes 11 patents [13–23] with inventor, year of application, patent number, and one of the characteristic abstracts describing the fundamental subject of the patent.

They concern co-rotating extruders with a self-cleaning profile, all relevant types of (single-, double-, and triple-flighted) mixing and kneading discs, modular designs, mixed-technology, backwards-pumping screw principle, and special designs for dewatering and evaporating.

It is interesting to note that

- the 20 years in which these 11 patents were issued is far shorter than the preliminary period mentioned above, and
- the material of the co-rotating extruder system is now precisely mathematically founded, is used in process engineering, and is being advanced by engineers.

1.2.2.1.2.1 Basic Patent of Threaded Screws

In view of its significance, an extract from the basic patent for the co-rotating threaded screw [13] is reproduced here (Figure 1.20 and Figure 1.21):

Erteilt auf Grund des Ersten Überleitungsgesetzes vom 8. Juli 1949
(WiGBl. S. 175)

BUNDESREPUBLIK DEUTSCHLAND

AUSGEGEBEN AM
12. JANUAR 1953

DEUTSCHES PATENTAMT

PATENTSCHRIFT

Nr. 862 668

KLASSE 39a GRUPPE 10 15

F 3192 XII / 39a

Dr. Walter Meskat, Dormagen und
Dipl.-Ing. Rudolf Erdmenger, Bergisch Gladbach
sind als Erfinder genannt worden

Farbenfabriken Bayer, Leverkusen-Bayerwerk

Vorrichtung zum Verkneten, Gelatinieren und Verpressen von plastischen Massen

Patentiert im Gebiet der Bundesrepublik Deutschland vom 7. Juli 1944 an
Der Zeitraum vom 8. Mai 1945 bis einschließlich 7. Mai 1950 wird auf die Patentdauer nicht angerechnet
(Ges. v. 15. 7. 51)
Patentanmeldung bekanntgemacht am 27. September 1951
Patenterteilung bekanntgemacht am 20. November 1952

PATENTANSPRÜCHE:

1. Vorrichtung zum Kneten, Gelatinieren und Verpressen von plastischen Massen, bei der zwei oder mehr oder ein- oder mehrgängige Schneckenwellen, die sich in einem dicht an den äußeren Umfang der Kämme anschließenden Gehäuse in gleichgerichtetem Sinne drehen, verwendet werden, dadurch gekennzeichnet, daß die Gewindenut einer Schnecke durch den eingreifenden Kamm der Gegenschnecke oder Gegenschnecken an den Flankenberührungsstellen vollständig oder nahezu vollständig längs einer Raumkurve abgedichtet ist, wobei das Gewindeflankenprofil so ausgebildet ist, daß die Flankenfläche in ihrer Verschneidung mit beliebigen ebenen Flächen senkrecht zur Schneckenachse Kreisbogenstücke ergibt, die den Radius $r =$ Achsabstand der beiden Schneckenwelen besitzen und den Kernkreis der Schneckenwelle tangieren.

2. Vorrichtung nach Anspruch 1, dadurch gekennzeichnet, daß die Gewindekammbreite einer Schneckenwelle stetig zunimmt, wobei sich die zugehörige Gewindenutbreite in der anderen Welle entsprechend vergrößert.

Figure 1.20 Basic patent for threaded screws – title page and patent claims

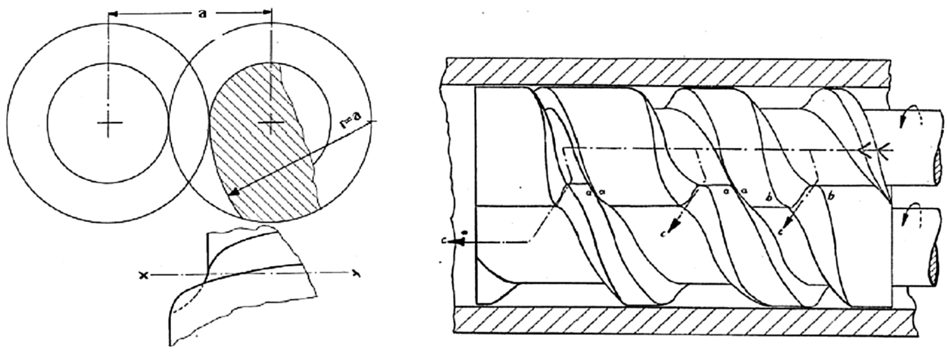


Figure 1.21 Basic geometry (illustration 3 according to patent)

The following items are of interest and worthy of mention:

- After the application in 1944, this patent was issued in West Germany in 1953 via a *"bridging act"* and was given a five-year post-war extension of validity (23 instead of 18 years, i.e., valid until 1967).
- The rapidity with which the language of technology changes is evident from the title given in 1944: "Vorrichtung zum Verkneten, Gelatinieren und Verpressen von plastischen Massen" (Apparatus for kneading, gelatinizing, and compressing of plastic masses).
- Just 20 years later, in the 1960s, the wording was as follows: "Vorrichtung zum Kneten, Plastifizieren und Extrudieren von Polymeren" (Apparatus for kneading, plastification, and extrusion of polymers).
- The first and the primary claims are extremely telling: Double-or multiple-shaft co-rotating extruders in single or multiple-flighted versions with the sealing profile, i.e., defined with the flank profiles in cross-section by circles with radius equal to the centerline distance (see Section 1.2.2.1.1).
- The second and final claim with the varied tip width along the axis with correspondingly varied groove widths of the neighboring shaft (for the purpose of increasing the mixing effect) has lost its significance with the subsequent invention of simpler kneading discs (see below).

In his paper [9], R. Erdmenger added material movements with explanations to Fig. 1 of the patent [13] (Figure 1.22): a is the purely axial movement (= theoretical conveying, see Section 1.2.2.1 above), b is the drag flow of a Newtonian fluid ($b < a$), and c is the minimal flow of a material adhering to the shafts ($c < b$).

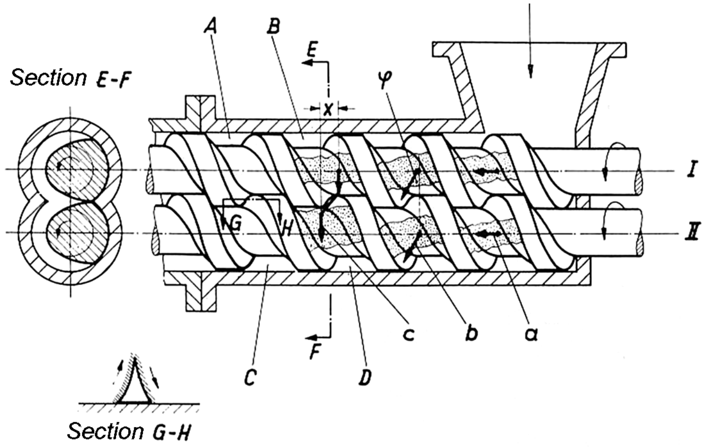


Figure 1.22 Multiple shaft co-rotating extruder system with full intermeshing and mutual cleaning of the shafts. There is a continuous connection between *A, B, C,* and *D,* etc.
The possible material movements in principle are as follows:
a) Purely axial shift of a rigid sliding body (e. g., wax)
b) Dragging of deforming substances (e. g., stringy liquids) in the direction of the arrow (angle φ), shearing in the gap, section G ÷ H.
c) Purely tangential conveying of materials adhered to the screws with smaller axial components (x) at transition from shaft I to shaft II.

1.2.2.1.2.2 Basic Patents for Kneading Discs, DBP [16], USP [17], DBP [20]

Kneading discs are prismatic bodies formed by axial displacement of the cross-section contour discussed above but without rotation common with screw threads (see Section 1.2.2.1.1).

Several kneading discs arranged on a core shaft create kneading elements (or kneading blocks) with special effects. The geometric variables of these kneading elements are the thickness of the individual discs and their offset angles with respect to one another, viewed in cross-section, and the resulting rotation of the individual kneading discs with the effect of a spiral staircase. This results in kneading, crushing, and shearing effects combined with active conveying (right-hand rotation), neutral, or reversing effects (left-hand rotation).

The same principles apply for the cross-sections of kneading discs as for the cross sections of their corresponding screw threads (see Section 1.2.2.1.1). The geometrical form is determined by number and depth of flights.

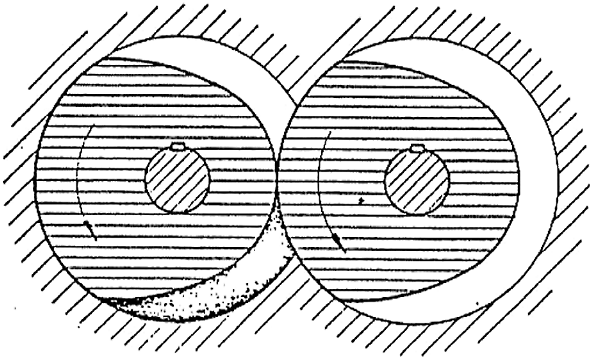


Figure 1.23 Single-flighted kneading discs

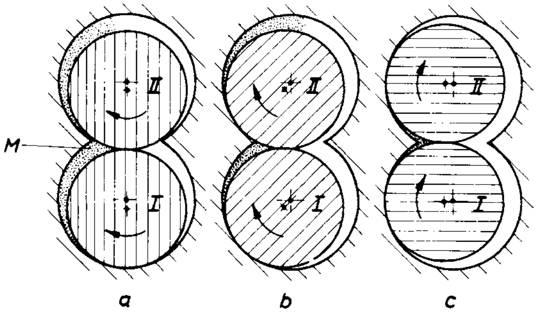


Figure 1.24 Operating method of eccentric, synchronous, co-rotating, circular discs: *a, b, c* three operating positions: mass *M* is crushed and sheared in the key during the quarter turn around their rotation axis described by each disc (*I* and *II*).

Figure 1.23 represents the normal case of a single-flighted kneading disc. Figure 1.24 shows the interesting special case of the single-flight, self-cleaning circular discs.

Figure 1.25 also shows the normal double-flighted kneading disc, also with Erdmenger's commentary. The practical limit for double-flighted elements is shown in Figure 1.26 with a small tip angle and large product volume (see Section 1.2.2.1.1).

Figure 1.27 explains the triple-flighted kneading disc and its effect according to R. Erdmenger [9].

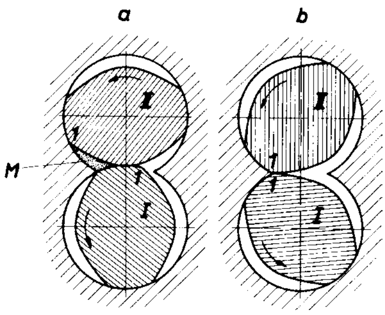


Figure 1.25 Double-flighted kneading discs operation of blunted lens-shaped discs
a) Commencement of kneading of deformable material (*M*)
b) End of the kneading phase
The mass *M* is crushed twice per revolution due to the co-rotation of discs *I* and *II* (approach of points 1–1) and escapes vertically to the indicated plane

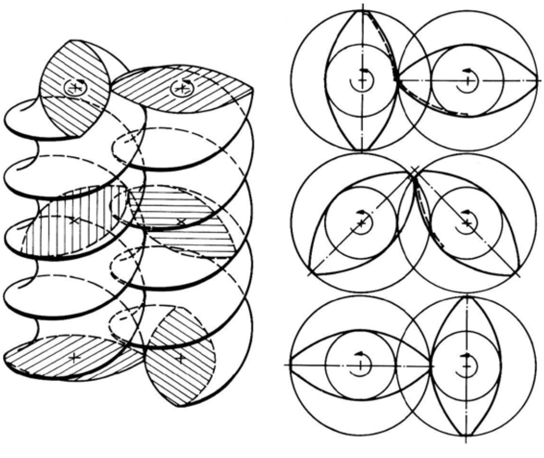


Figure 1.26 Practical limit for double-flighted elements

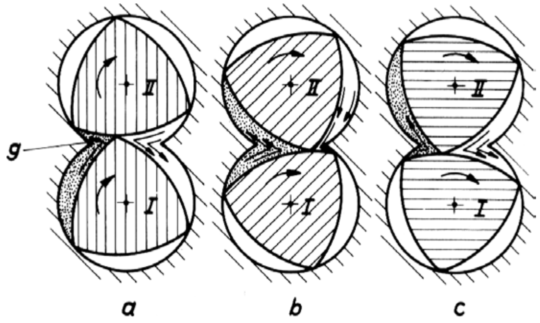


Figure 1.27 Operating method of 3-point kneading discs: *a, b, c* three operating positions. The mass *M* is forced to flow around the sharp barrel ridge *G* three times per revolution by the synchronous rotation of the co-rotating discs *I* and *II* wherein it is sheared to an extreme degree.

1.2.2.1.2.3 Basic Patents for Modular Design

Further patents describe the modular principle for different screw and kneading elements threaded and clamped to a core shaft. The benefits are striking:

- Formation of different functional zones along the machine with optimized technical processes.
- Variation of the screw geometry for tests and at start up.
- Adjustment to subsequent process changes.
- Typifying and standardization of screw and kneading element production.
- Simplification and cost savings in spare parts acquisition.

These benefits resulted in the USP [21] with priority 1959 for R. Erdmenger. The modular design is illustrated in Figure 1.28 below with a combination of different consecutive screw and kneading zones and in Figure 1.29 as a modular assembly diagram.

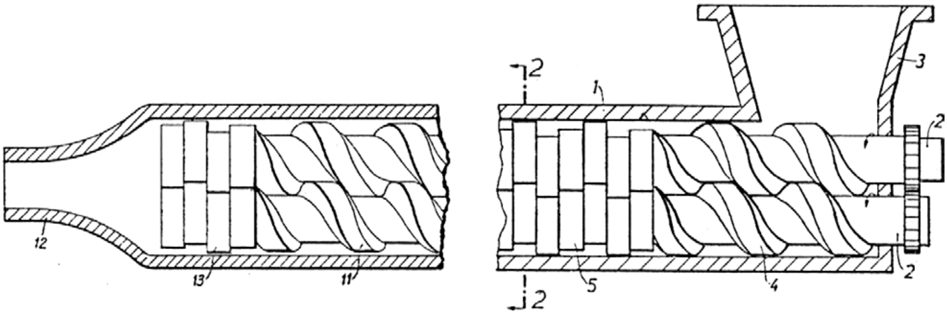


Figure 1.28 Modular principle

Figure 1.29 Modular assembly diagram

W. Meskat und J. Pawlowski obtained a German patent (DBP) [18] by 1950 for a co-rotating extruder with sections featuring localized backward-feed with respect to the primary feed direction. This was achieved by backward pumping screws, i.e., by right-to-left hand rotation combinations in the screw geometry whereby specific mixing effects are achieved. Figure 1.30 shows this apparatus in detail.

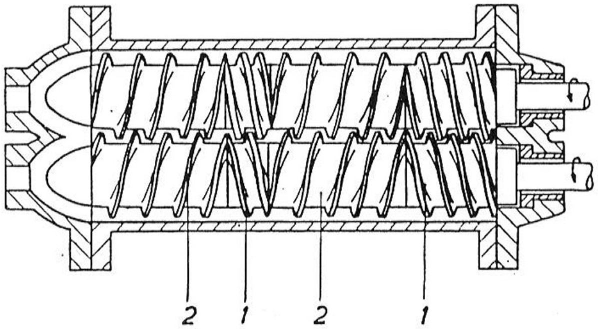


Figure 1.30 "Backward pumping screw" with left/right hand thread

These three groups of patents, namely, the widely used *threaded screws,* the *kneading elements,* and the *modular design* principle paved the way for the development of a highly effective new machine type for process engineering and plastics technology.

At this point it is also worth mentioning the (modified) comment made by H. Herrmann [36]:

"W. Meskat, A. Geberg and R. Erdmenger's idea of a co-rotating and closely intermeshing twin screw of 1944 was readdressed and turned into a complete and well-founded geometrical solution. Since this time, it has been possible to talk of *close meshing* and *self-cleaning* co-rotating extruder machines."

1.2.2.2 Pioneering Period

R. Erdmenger had worked together with A. Geberg since 1943 in W. Meskat's twin-screw core team in Wolfen, and he pursued this work intensively after 1945 for Bayer AG in Leverkusen, achieving success and acclaim with his team. His work comprised three fundamental components:

1. The necessary in-house *machine development* for co-rotating extruders.
2. The use of these machines in *chemical processes* and/or the realization of innovative chemical processes using co-rotating extruders.
3. The *issue of the license* for this machinery system in the face of increasing demand.

1.2.2.2.1 Machine Development

With respect to the first point it is obvious that laboratory screws, developmental experiments, and prototype product machines were developed with the workshop technology available in-house. Here in particular, Erdmenger's university training in mechanical engineering and his leadership were an essential driving force on the road to success. The team produced the *DA/DK* = 32/24 mm laboratory screw as a Bayer house model around 1948.

Figure 1.31 illustrates another example of a highly specialized machine from the pioneering period. Produced around 1955, it has a degressive pitch in the transport direction, which, surprisingly, was cut from the solid feedstock.

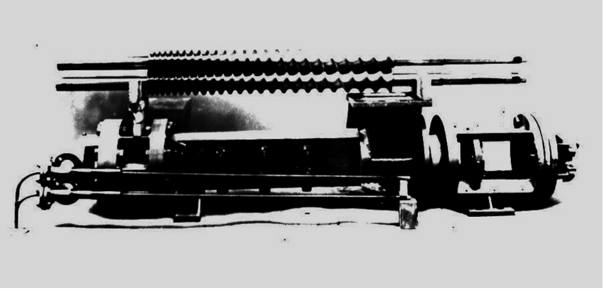


Figure 1.31 Pioneering screw, circa 1955, with degressive pitch

1.2.2.2.2 Use in Chemical Processes

The application of co-rotating extruders in chemical processes only stood a chance, if the new components of the co-rotating extruder made the product

- *more economically viable,* or
- to a *higher quality,* or
- *more environmentally friendly*.

This is taken into account in an engineering sketch drawn by R. Erdmenger himself in 1953 of a chemical screw process (Figure 1.32). From today's point of view, the last two illustrations display the historical patina and archaic simplicity of engineering times long past. The same also applies for Figure 1.33 which shows a somewhat rustic experimental center from 1957.

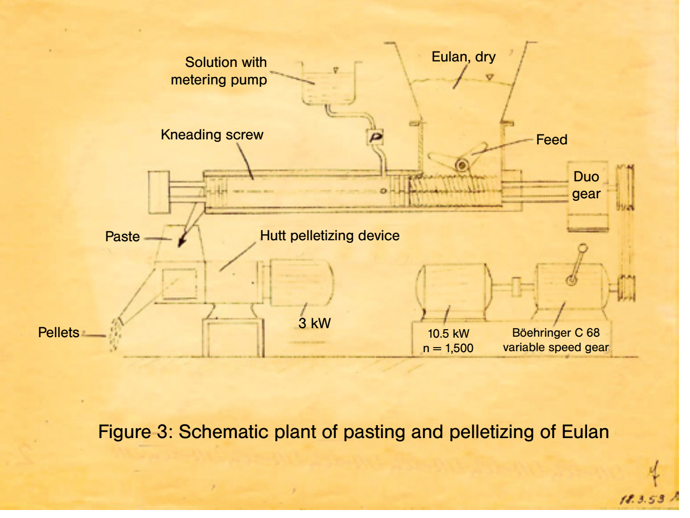


Figure 1.32 Pioneering process according to R. Erdmenger 1953

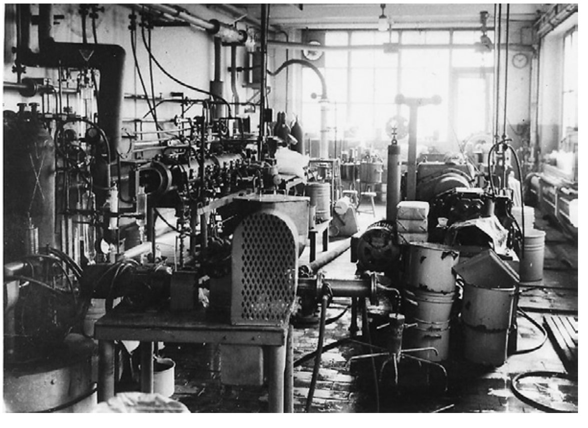


Figure 1.33 Experimental center, circa 1957

1.2.2.2.3 Licensing

Licensing of the new technology came to fruition in 1953. After intensive preliminary work and negotiations with several mechanical engineering firms, the noted company Werner und Pfleiderer in Stuttgart obtained the exclusive worldwide license (as is so often annoying for the inventor, nine years had passed since the initial invention in 1944). Although the licensee today operates under the name "Coperion Werner & Pfleiderer GmbH & Co. KG, Stuttgart",[1] we will refer to them as "Werner & Pfleiderer" in the following.

[1] The company name has changed to Coperion since this chapter was written.

A key reason for the issue of the license was that in-house production in chemical workshops was no longer possible for screw diameters beyond 120 mm. At the same time, there was a demand for higher quality machinery.

1.2.2.2.4 Recognition for R. Erdmenger

The development period of the co-rotating extruders, which was shaped by R. Erdmenger (he is portrayed in Figure 1.35), is considered the pioneering period for this technology today.

Figure 1.34 SPE's "Distinguished Service Award" for R. Erdmenger in 1986

Figure 1.35 Portrait of Rudolf Erdmenger

After his retirement, Erdmenger received two awards in the US:

- the "Distinguished Service Award" of the Society of Plastics Engineers "SPE" (Figure 1.34), and
- introduction into the University of Akron/Ohio's "Hall of Fame".

1.2.2.3 New High-Viscosity Technology with Co-Rotating Extruders

Soon after the patents cited above were issued, publications about the new types of co-rotating extruders and their applications began to appear in increasing numbers. The secondary literature also cites further publications [24–35] from the period between 1951 and 1974, many of which were authored by the licensors: Bayer, i.e., predominantly R. Erdmenger and the licensee: Werner und Pfleiderer, i.e., H. Herrmann. These publications increasingly pushed process engineering and the various uses of the co-rotating extruder.

1.2.2.3.1 Screw Machines in Process Engineering

It is to the great credit of H. Herrmann that, after the licensing process and alongside his primary developmental role at Werner & Pfleiderer, he edited the standard work on this topic, published in 1972 [36]. In this work, two further important points are worth emphasizing: on the one hand, the mechanical engineering description and historical classification of all known screw types and on the other hand, the appreciation of the co-rotating extruder along with their process engineering application areas and operating methods.

1.2.2.3.2 Similarity Theory for Screw Machinery

J. Pawlowski extended the knowledge base and deepened understanding of the physical functions and operating methods of screw machinery considerably through the development of the *similarity theory* and its application to these machines [37–39]. His work‘s significant consequences:

- Seven independent, dimension-specific values for filled screws were reduced to just three dimensionless parameters for throughput, pressure, and power (Figure 1.36).
- The dependencies of these dimensionless parameters for Newtonian fluids can be simplified to two linear equations (Figure 1.37) for the target values (measured on a co-rotating extruder) of pressure (Figure 1.38) and power (Figure 1.39). These straight lines are fixed by their axial sections A_1, A_2 for pressure and B_1, B_2 for power. The value of these “profile parameters” depends on the “internal geometry” of the screw, i. e., on the shape of the profile (see 1.2.2.4.1) and on the screw type (single shaft, multiple shaft, co-rotating, counter-rotating). The “external geometry” (d, L) is already incorporated into the three dimensionless parameters (Figure 1.36).

$\dot{V}$	*Volumetric flow*
n	*Screw speed*
Δp	*Pressure differences*
η	*Viscosity*
P	*Drive power*
d	*Screw barrel internal diameter*
L	*Screw length*

$$\frac{\dot{V}}{n d^3} \qquad \frac{\Delta p\, d}{\eta n L} \qquad \frac{P}{\eta n^2 L d^2}$$

Figure 1.36 Reduction of dimension specific factors (7 → 3) according to J. Pawlowski [37], (for Newtonian media)

$$\frac{1}{A_1} \cdot \frac{\dot{V}}{nd^3} + \frac{1}{A_2} \cdot \frac{\Delta p d}{\eta n L} = 1$$

$$\frac{1}{B_1} \cdot \frac{\dot{V}}{nd^3} + \frac{1}{B_2} \cdot \frac{P}{\eta n^2 L d^2} = 1$$

Profile parameter: A_1, A_2, B_1, B_2:
Axial sections of straight-line equations

Figure 1.37 Linear pressure and power characteristic of filled screws

The four profile parameters are determined experimentally in a far less time-consuming process. The measurements for *co-rotating extruders* from [40] in Figure 1.38 and Figure 1.39 show that Pawlowski's similarity method is valid in terms of flow engineering [37] even for this complex screw type.

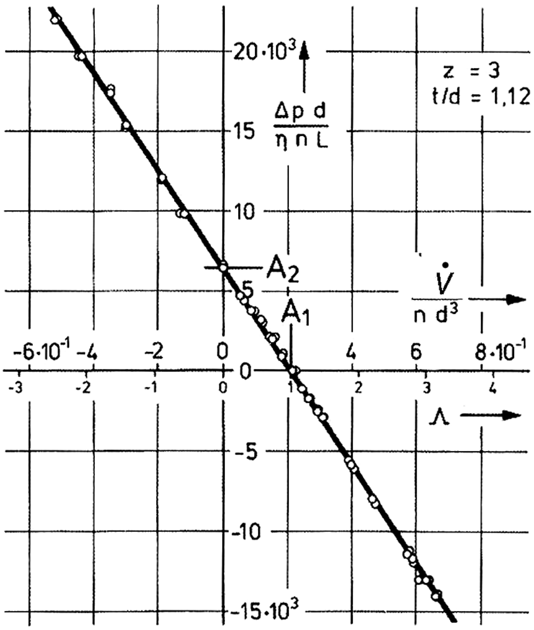


Figure 1.38 Pressure measurements on a co-rotating extruder

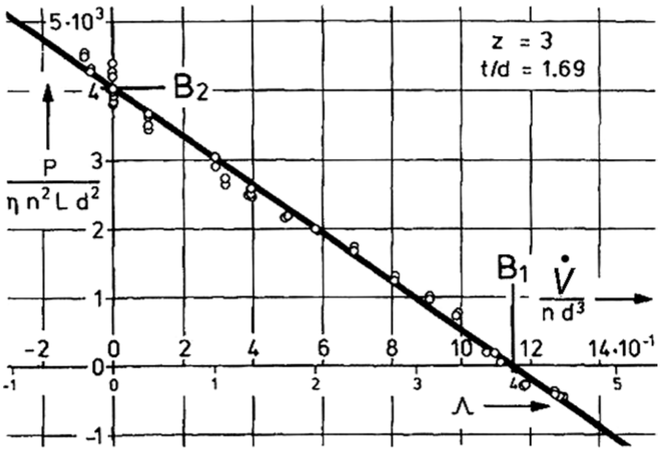


Figure 1.39 Power measurements on a co-rotating extruder

The same data, determined by not too complex means, can also be used to answer further questions, e.g. relating to the efficiency of the pressure build-up. Figure 1.40 illustrates the "product stress" (the reciprocal value of the pump efficiency) comparing counter-rotating and co-rotating extruders [40], i.e., two substantially different machines.

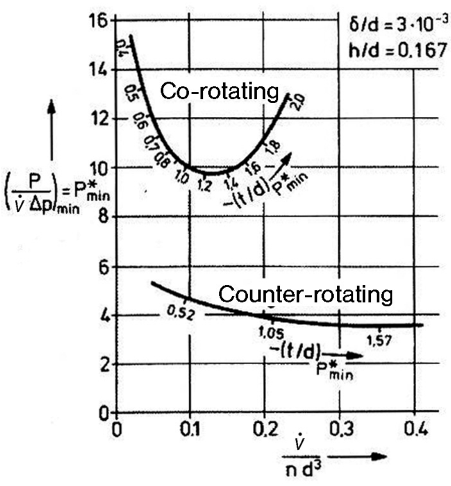


Figure 1.40
Energetic optimization, i.e., "minimal stress" for co-rotating and counter-rotating screws

1.2.2.3.3 Versatile High-Viscosity Processes

The high-viscosity processes developed during and after the pioneering period and the applications discovered for high-viscosity machines [8] are as striking as they are varied.

Table 1.1 Applications of High-Viscosity Machines

Process-orientated tasks	Product groups
Mixing, compounding, kneading, pasting, dissolving	Plastics, dyes, fibers, silicon polymer
Expelling dewatering	Rubbers
Evaporating, releasing, residual degassing	Plastics, rubbers, adhesives
Polymerization, polycondensation, polyaddition, and other reactions	Thermoplastic polyurethanes, silicone polymers
Crystallization, melting	Pesticides, organic matter
Extruding, forming, pelletizing	Plastics, rubbers

The process engineering tasks are classified according to the product groups for which they are used. There are four main areas: material mixing, material separation, reaction, and phase transformation. The common factor of all the processes in Table 1.1 is of course the high-viscosity phase and consequently the specific “difficulties” of the machinery (technical design, dimensioning with respect to forces, torques, drive power, pressures).

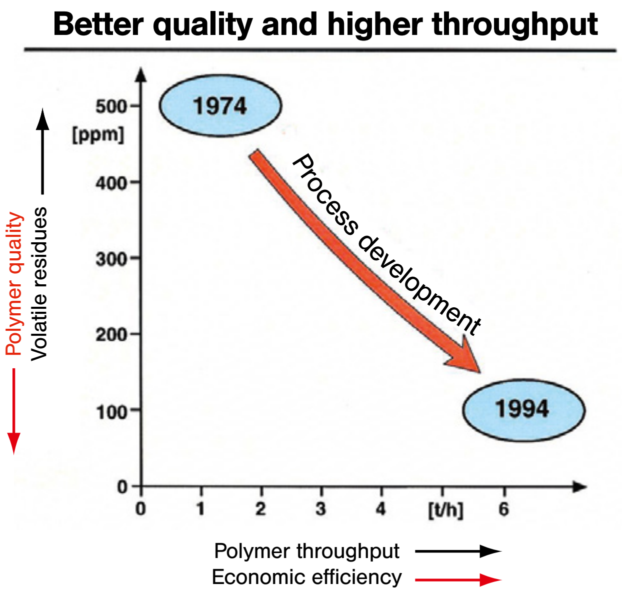


Figure 1.41
Goals of process optimization

Along with the work within the parameters of the basic operations, the process engineer has to investigate important processes in-depth to develop and optimize those processes (Figure 1.41) [8]. This involves meeting the constantly increasing market demand for higher quality while maintaining economic viability, in other words increasing throughput. From a physical point of view, however, the residual content of volatile materials increases dramatically as the throughput increases. Therefore, specific process engineering measures are required to reach the goal of increasing throughput by a factor of six while reducing the residual content by a factor of five (Figure 1.41).

1.2.2.4 Special Developments from Bayer-Hochviskostechnik (High Viscosity Technology Group)

1.2.2.4.1 Extended Kinematics, Profile Geometries

During the pioneering time of co-rotating extruders, predominantly graphical methods were applied for the basic geometry illustrated in Section 1.2.2.1.1 and the technical design of new machines, but the advances in automated computing technology soon proved to be ideal for the design of co-rotating extruders. Here, the internal geometry of the screw (Figure 1.42) is determined by six independent geometrical factors:

1. Internal barrel diameter d
2. Centerline distance a
3. Tip-wall clearance δ
4. Screw-screw clearance S
5. Screw pitch t
6. Number of flights Z

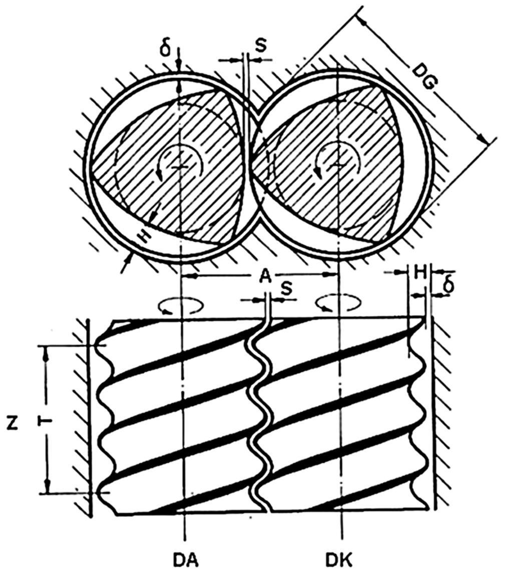


Figure 1.42 Internal geometry of the co-rotating extruder with dimensioning

The clearances δ and S are not required for the fully-wiping screw (see Section 1.2.2.4.2). This leaves four independent factors. Other six-fold combinations of independent geometrical values can also be used.

The application of the basic geometry by computer for a screw described in this way (see Section 1.2.2.1.1) results in the calculation of the profile curves in cross-section and in longitudinal section and, for example output for manufacture. Process engineering target values, such as the usable product volume and all surfaces, are also determined.

1.2.2.4.2 Clearance Strategies

"No screw without clearances": there are five reasons for this motto:

- The natural surface roughness of the screw and barrel material with clearances $S = 0$ and $\delta = 0$ leads to "cold welding" and therefore to erosion and blockages. This is unacceptable and clearances are therefore required.
- All production methods involve inherent production tolerances that must be ensured by the application of respectively larger clearances.
- The quality of the axial bearings of the two shafts in the duo-gear as well as that of the rotation angle allocation leads to tolerances and clearances in the screw profile.
- Occasional irregularities in the heating process or torsional stress on the two shafts can lead to mutual shifting and thus require clearances.
- Process engineering aspects can also require particular clearances if, for example, intensive shearing in the tip zones affects product quality.

These different reasons for the need for clearances led to different strategies in their implementation:

The clearances δ (tip–wall) and S (tip–base of neighboring screw) should be set as trivial because they are radially effective.

- In the pioneering period of the co-rotating extruder, technical designs corresponded exactly with the basic geometry, with the result that the two shafts tended to move apart somewhat in the actual machines *("centerline distance enlargement")*. Ideally S was obtained at the base of the screw while at the outside of the flank, particularly with small pitches, varying flank clearance occurred, sometimes much smaller than the required S (with a consequential danger of collision).
- A considerably better clearance strategy was realized graphically or, as described in Section 1.2.2.4.1, the *"planar offset"*. In the longitudinal section profile curve of the fully wiping screw ($S = 0$) calculations are carried out based on a $S/2$ orthogonally-shifted longitudinal section profile curve (Figure 1.43) and are retroceded to the cross-section profile. The disadvantages of method 1: "centerline distance enlargement" are largely reduced by the clearance strategy 2: "planar offset".

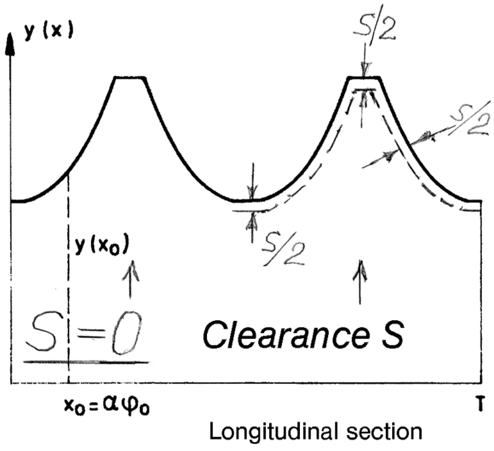


Figure 1.43 Planar offset

- The corresponding screws cut against one another through a spatial curve. Therefore, the effective clearance orientated to the spatial curve is relevant as it is in view of the self-wiping effect and the product stress. The result is the "*spatial offset*" with the aforementioned advantages.

The clearance strategies are compared in Table 1.2.

Table 1.2 Evaluation of the clearance strategies

Clearance Strategy	Grade	Flank effect
Fully wiping screw $\delta = 0$, $S = 0$	1	"Eroding"
"Centerline distance enlargement" $S \neq$ constant	2	Danger of collision
"Planar offset" $S \approx$ constant	3	Good compromise
"Spatial offset" $S \equiv$ constant	4	Perfect solution

The clearance considerations above apply for constant screw geometry along the axis and particularly for a constant pitch. Modular screws with elements with different pitches create the following dilemma:

With constant flank clearances along the entire machine, the contact points of different element pitches exhibit slight differences in their cross-section contours. On the other hand, applying congruent cross-section contours and therefore identical element contact points to avoid this results in varying flank clearances.

See Chapter 4 and Section 1.4 for an overview of computational programs for process screws. See [41] for details about flow simulation using "CFD".

1.2.2.5 Developments after Licensing

After the license was awarded to Werner & Pfleiderer (Section 1.2.2.2.3) and after an initial warm-up phase, machinery and process engineering underwent dramatic development. This took place during the years of industrial development and the simultaneous advances in the areas of polymer chemistry and plastics engineering that were taking place at the same time (e.g., compounding technology). Five major developments characterize this boom:

1. The increase in production quantity of co-rotating extruders; by the beginning of the 1960s, Werner und Pfleiderer had delivered the 100th ZSK 83 model of this machine.
2. The modular technology was developed both for the internal screw geometry (Figure 1.44) and for whole machines (Figure 1.45).
3. The trend towards large machines (Figure 1.46) began soon after, leading to today's ZSK 380 "mega-compounder" with a throughput of up to 50 t/h.
4. Modified "light duty" screws were designed for special chemical applications (for example see Figure 1.47).
5. Approximately 5000 co-rotating extruders of all types and sizes have been produced so far by Werner & Pfleiderer.

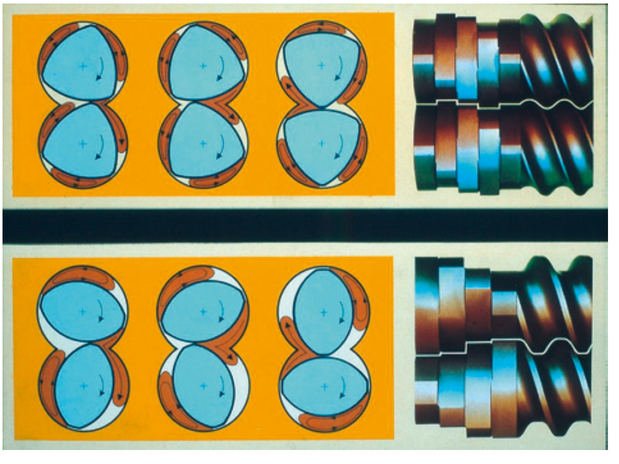


Figure 1.44 Modular technology in screws (Courtesy: Werner & Pfleiderer)

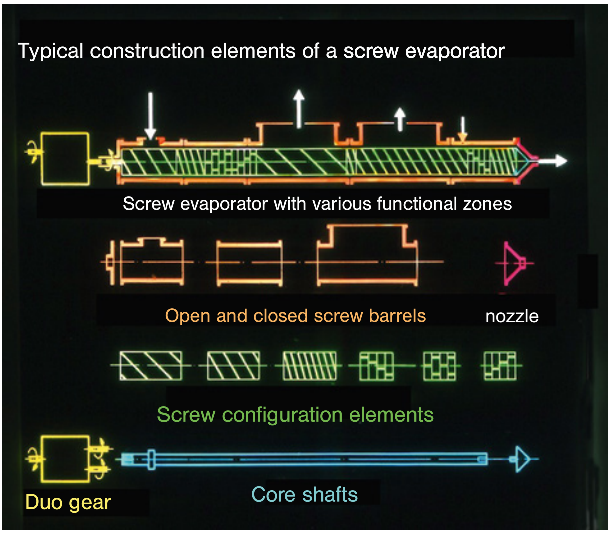


Figure 1.45 Overall machine comprising typical modular components

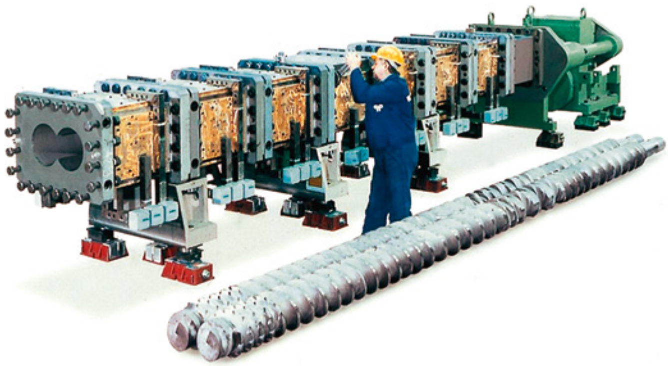


Figure 1.46 Large co-rotating extruder: Megacompounder ZSK 340 (Courtesy: Werner & Pfleiderer)

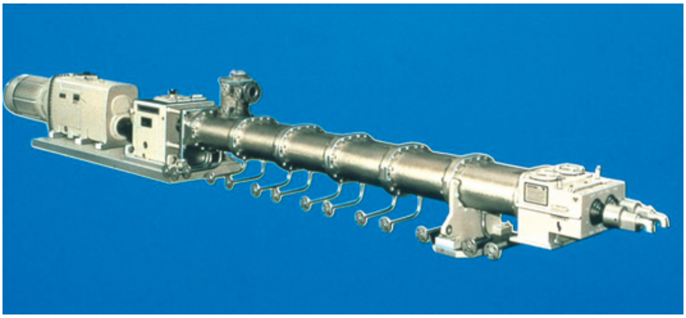


Figure 1.47 Light duty co-rotating extruder: ZDSW 160 (Courtesy: Werner & Pfleiderer)

It took a well-established mechanical engineering company to turn this development effort into a successful engineering and commercial enterprise. Even the individual areas of research and development, testing, project planning, technical design, production, assembly, commissioning, sales, and customer service now required teams with management and technical expertise, while during the pioneering period a small group developed in this field (Section 1.2.2.2).

Another feature of the post-licensing period is the increase in published university research and publications from mechanical and chemical engineering companies. This includes H. Herrmann's standard work of 1972 [36], referred to in Section 1.2.2.3.1, along with other selected examples [42, 43].

1.2.2.6 Developments after Expiration of the Primary Patents

Once the co-rotating extruder had become the standard element for plastics conditioning and processing, compounding in other words, and the patents referred to in Section 1.2.2.1.2 had expired (approximately 1970), the co-rotating principle was adopted by numerous mechanical engineering companies. Today, approx. 50 companies around the world can supply small- or medium-sized (approx. < 120 mm) screws. However, just five are able to supply large screws of 120 mm to 380 mm (estimated values).

The "patent vacuum" has also prompted new applications from several areas. Apparatus patents are among the foremost of these, i. e., numerous variants of innovative screw, mixing, and kneading elements from mechanical engineering companies, while process patents employing co-rotating extruders are proposed by the chemical industry.

We are also witnessing a considerable increase in new specialized literature. The most important of these is the standard work "Twin Screw Extrusion" by J. L. White [44]. It is a rich source of information, both about the historical development and the state-of-the-art technology, as well as about patent literature and specialized publications. A few examples [45, 46] from the wide-ranging specialized literature on the subject of co-rotating extruders should be mentioned here.

Plastics technology and co-rotating extruders have undergone dramatic developments which, to a certain extent, have been synchronous and mutually supportive. Plastics technology has profited from the increasing potential of the co-rotating extruder, while polymer technology has itself been a hothouse for advances in co-rotating extruders. We can therefore conclude: There is hardly a kilogram of plastic today that has not encountered a co-rotating extruder somewhere on its journey between polymerization and processing.

Figure 1.48 shows the dynamic development of the co-rotating extruders with the increase in volumetric throughput over time. It also includes the milestones in the development and process engineering operations and their respective starting points.

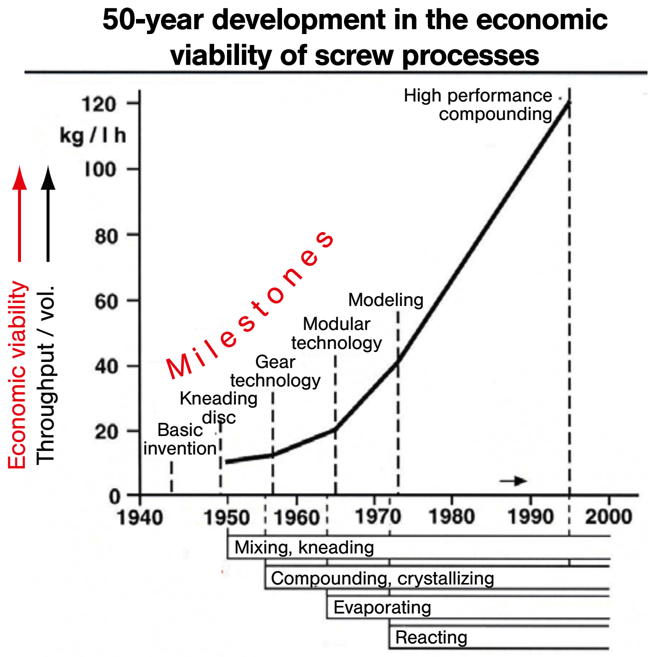


Figure 1.48 Dynamic development of the co-rotating extruders

References for Section 1.2.2

[1] Personen Lexikon 1 (A–L), Chronik-Verlag, p. 76

[2] Coignet, F., US Patent 93035 (1869)

[3] Wünsche, A., German Patent 131392 (1901)

[4] Easton, R. W., GB Patent 109663 (1916)

[5] Nelson, W. K., US Patent 1868671 (1931)

[6] Pease, F. F., US Patent 2048286 (1933)

[7] Colombo, R., Italian Patent 370578 (1939)

[8] Wagner, W., 50 Jahre Verfahrenstechnik im Bayer-Konzern 1948–1998 – Rückschau und Ausblick. Bayer-Jubiläumsschrift der ZT-Technische Entwicklung

[9] Erdmenger, R., Schneckenmaschinen für die Hochviskostechnik, Bayer AG (1978)

[10] Meskat, W., Geberg, A., Erdmenger, R., IG internal reports (1944)

[11] Erdmenger, R., Neidhardt, S., Bayer internal reports (1948)

[12] Erdmenger, R., Bayer internal reports (1948/51)

[13] Meskat, W., Erdmenger, R., DBP 862668 Gleichdrall-Doppelschnecke mit Dichtprofil. Basic patent for the threaded screw. Priority: 1944 (transferred to West Germany: 1953). Extracts from this key patent are included in the text and its importance emphasized

[14] Meskat, W., Erdmenger, R., DBP 872732, Gleichdrall-Dreifachschnecke mit Dichtprofil zum Abpressen. Priority: 1944 (transferred to West Germany: 1953)

[15] Erdmenger, R., DBP 815641, Gleichdrall-Doppelschnecke mit Sperrbarrieren zum Mischen (1949)

[16] Erdmenger, R., DBP 813154, Gleichdrall-Knetscheiben mit Dichtprofil, eingängig und zweigängig sowie Sonderfall Kreis-Exzenter. Basic patent for the kneading element (1949)

[17] Erdmenger, R., USP 2670188 as above: DBP 813154, however, without double-flighted kneading element (1950)

[18] Meskat, W., Pawlowski, J., DBP 949162 Gleichdrall-Doppelschnecke mit Dichtprofil und “Bremsgewinde” (rechts-links-Kombination) zum Mischen (1950)

[19] Erdmenger, R., Neidhardt, S., DBP 915689 Gleichdrall-Doppelschnecke mit Dichtprofil und “Rückwärtsentgasung” über “Seitenschnecke” (1951)

[20] Erdmenger, R., DBP 940109, (1953) = USP 2814472, (1954), Gleichdrall-Knetscheiben mit Dichtprofil, dreigängig, Knetelemente, Erweiterung

[21] Erdmenger, R., USP 3122356, Gleichdrall-Doppelschnecke mit Dichtprofil und modularer “Baukasten-Bauweise” (1959)

[22] Erdmenger, R., Oetke, W., DBP 1111154, Vierwellenschnecke mit Dichtprofil für Verdampfungsprozesse (1960)

[23] Erdmenger, R., USP 3254367, Gleichdrall-Doppelschnecke mit Dichtprofil und “Schulter” im Schneckenkanal (1963)

[24] Riess, K., Meskat, W., Schneckenmaschinen für die Verfahrenstechnik zähflüssiger und plastischer Massen, *Chem.-Ing.-Tech.* (1951), 23 (9/10), pp. 205–212

[25] Riess, K., Erdmenger, R., Der heutige Stand der Technik kontinuierlicher Press- und Knetverfahren in der chemischen und verwandten Industrie, *VDI-Z.* (1951), 95 (19/20), pp. 633–638

[26] Erdmenger, R., Stoffzerkleinernde Mischprozesse, *Chem.Ind.* (1953), pp. 513–518

[27] Riess, K., Probleme kontinuierlicher Verfahren in der Verbrauchsgüterindustrie, *Chem.-Ing.-Tech.* (1955), 27, pp. 457–464

[28] Erdmenger, R., Zur Entwicklung von Schneckenverdampfern, *Chem.-Ing.-Tech.* (1962), 34, pp. 751–754

[29] Herrmann, H., Entwicklungstendenzen bei Aufbereitungsmaschinen für die Kunststoff-industrie, *Chem. Ind.* (1962), pp. 603–606

[30] Erdmenger, R., Mehrwellenschnecken in der Verfahrenstechnik, *Chem.-Ing.-Tech.* (1964) 36 (3), pp. 175–185

[31] Herrmann, H., Die zweiwellige Knetscheiben-Schneckenpresse ZSK 160, *Kunststoff und Gummi* (1964), pp. 217–223

[32] Herrmann, H., Das Aufbereiten von Kunststoffen in Schneckenmaschinen, *Kunststoffe* (1965), pp. 845–849

[33] Herrmann, H., Mischungsverhältnisse und Selbstreinigung in einwelligen und zweiwelligen Schneckenmaschinen, *Chem.-Ing.-Tech.* (1966), pp. 25–29

[34] Erdmenger, R., Ullrich, M., Untersuchungen an einem Schneckenverdampfer, *Chem.-Ing.-Tech.* (1970), 42(1), pp. 1–5

[35] Erdmenger, R., Entgasen hochviskoser Flüssigkeiten, *Masch.markt* (1974), 80 (1, 2–6, and 10), pp. 148–152

[36] Herrmann, H., *Schneckenmaschinen in der Verfahrenstechnik*, Springer-Verlag, Berlin, Heidelberg, New York (1972)

[37] Pawlowski, J., *Die Ähnlichkeitstheorie in der physikalisch-technischen Forschung* Springer-Verlag, Berlin, Heidelberg, New York, (1971)

[38] Pawlowski, J., *Transportvorgänge in Einwellen-Schnecken* Verlag Salle u. Sauerländer, Frankfurt/Main (1990)

[39] Pawlowski, J., *Veränderliche Stoffgrößen in der Ähnlichkeitstheorie*, Verlag Salle u. Sauerländer, Frankfurt/Main (1991)

[40] Ullrich, M., two papers in VDI-K-proceedings: Optimierung des Compoundierprozesses durch Rezeptur- und Verfahrensverständnis, VDI-Verlag, Düsseldorf (1997)

[41] Kohlgrüber, K., Beck, D., two papers in VDI-K-proceedings: Optimierung des Compoundier-prozesses durch Rezeptur- und Verfahrensverständnis, VDI-Verlag, Düsseldorf (1997)

[42] Werner, H., Das Betriebsverhalten der zweiwelligen Knetscheibenpresse vom Typ ZSK bei der Verarbeitung von hochviskosen Flüssigkeiten, Technical University Munich, Dissertation (1976)

[43] Herrmann, H., Burkhardt, U., Vergleichende Funktionsanalyse dicht kämmender Gleichdrall- und Gegendrall-Doppelschnecken, *Kunststoffe* (1978), 68 (1), pp. 19–26

[44] White, J. L., *Twin Screw Extrusion*, Hanser, Munich (1990)

[45] VDI-K conference proceedings: Optimierung des Compoundierprozesses durch Rezeptur- und Verfahrensverständnis, VDI-Verlag, Düsseldorf (1997)

[46] VDI-K conference proceedings: Der Doppelwellenextruder, Grundlagen und Anwendungen, VDI-Verlag, Düsseldorf (1998)

■ 1.3 General Overview of the Compounding Process: Tasks, Selected Applications, and Process Zones

Reiner Rudolf

1.3.1 Compounding Tasks and Requirements

The properties of polymers need constant refinement to meet the constantly increasing demands on plastic parts. Because the development of new polymers is steadily decreasing [1], deliberate modification of the properties of a base polymer by means of additives and/or blending with other polymers is becoming increasingly important. This is the main task of compounding.

In Europe, approximately 7 million tons of compounds and 1 million tons of masterbatches were consumed in 2010. The European compounding and masterbatch market is shown in Figure 1.49.

The requirements of the compounding process are characterized by

- Increasing throughputs
- Decreasing batch sizes
- Increasing product variety
- Increasing quality requirements,
- Increasing filler contents
- New products (e. g., nano-filler materials, modified and blended polymers)

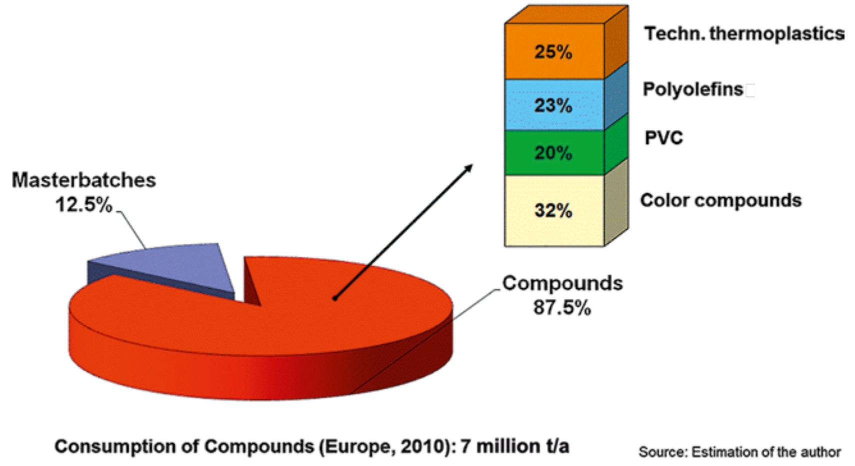


Figure 1.49 Compound and masterbatch market in Europe 2010

Today, compounding is predominantly carried out with co-rotating twin-screw extruders with constantly increasing available drive powers, torques, and screw speeds.

In particular, increasing throughput means increasing the screw speed, which in turn leads to

- Higher thermal and mechanical polymer stress ($q = \eta \cdot \dot{\gamma}^2$; $\tau = \eta \cdot \dot{\gamma}$)
- Shorter available processing times $\left(t_V = f\left(n, \dot{M}\right)\right)$

This increases the risk of loss of product quality due to a decrease in the molar mass, thermal inhomogeneity, and unmelted recipe components. Hence, the extruder and screw concepts need to be constantly optimized and adapted to avoid quality loss.

Typical compounding tasks include

- Reinforcing polymers
  - Incorporation of fibers (glass, carbon, or natural fibers)
- Modification of thermoplastics to achieve high-impact resistance
  - Blending with rubber elastic components
- Improving the dimensional stability and compression strength of polymers
  - Incorporation of inorganic fillers, glass beads
- Improvement of flow, mold release, and flame-retardant behavior of polymers
  - Incorporation of low-viscosity substances
- Production of polymer blends
  - Mixing compatible or incompatible polymer melts
- Coloring polymers
  - Incorporation of pigments, masterbatches, or liquid dyes

- Improvement of chemical/physical stability of polymers
  - Incorporation of low-viscosity stabilizers, antistatic agents.

The consumption of mineral fillers in Western Europe for thermoplastics processing alone was 1.3 million tons in 2015 [2]; a breakdown is shown in Figure 1.50.

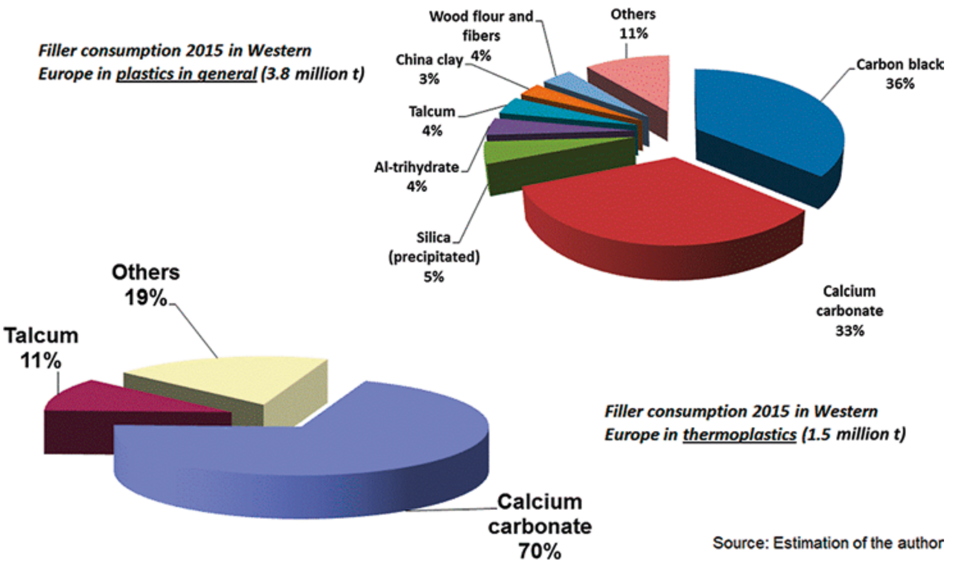


Figure 1.50 Consumption of mineral fillers for thermoplastic processing in Western Europe 2015

1.3.2 Tasks and Design of the Processing Zones of a Compounding Extruder

The various processing zones of a twin-screw extruder are arranged in series, as illustrated in Figure 1.51. Each processing step is linked to the next. Therefore, the different steps cannot be considered independently from each other. If, for example, the speed or throughput is changed, this inevitably affects all process zones. As will be explained below, this can be advantageous for one process zone, but it can have negative effects for another.

Furthermore, the process zones cannot be strictly separated. Dispersion processes, for example, already take place in the plasticizing zone; the incorporation of fibers dosed into the melt takes place not only in the designated dispersing zone but also in the discharge zone and in partially-filled screw channels.

Analyzing the unit operations in the extruder to a satisfactory degree is only possible when sufficient information about the rheological and thermodynamic properties of the polymers and polymer compounds is available. However, providing these data is very difficult, particularly in zones with considerable changes in state. Therefore, it is frequently necessary to refer back to model investigations and trials [3].

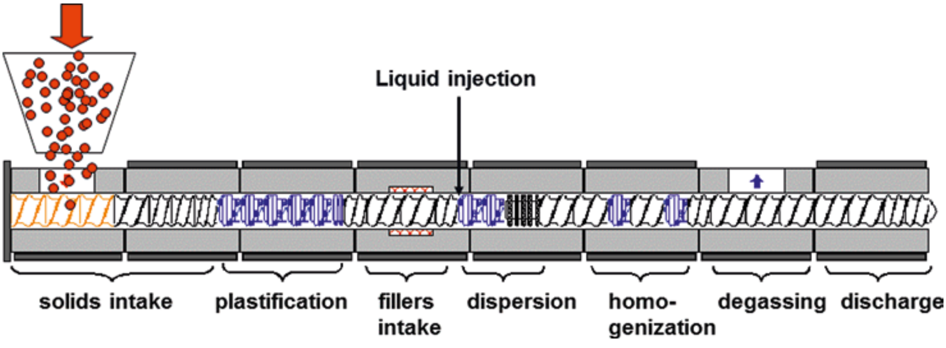


Figure 1.51 Processing zones of a twin-screw extruder

Figure 1.52 compares the independent setting parameters of the compounding process with the process values. Other than with a single-screw extruder, the throughput rate can be chosen independently of screw speed.

The process parameters in the extruder are variable in axial as well as radial direction. As a rule, however, only integral values along the entire extruder can be measured, e. g. the melt temperature in the emerging melt strand.

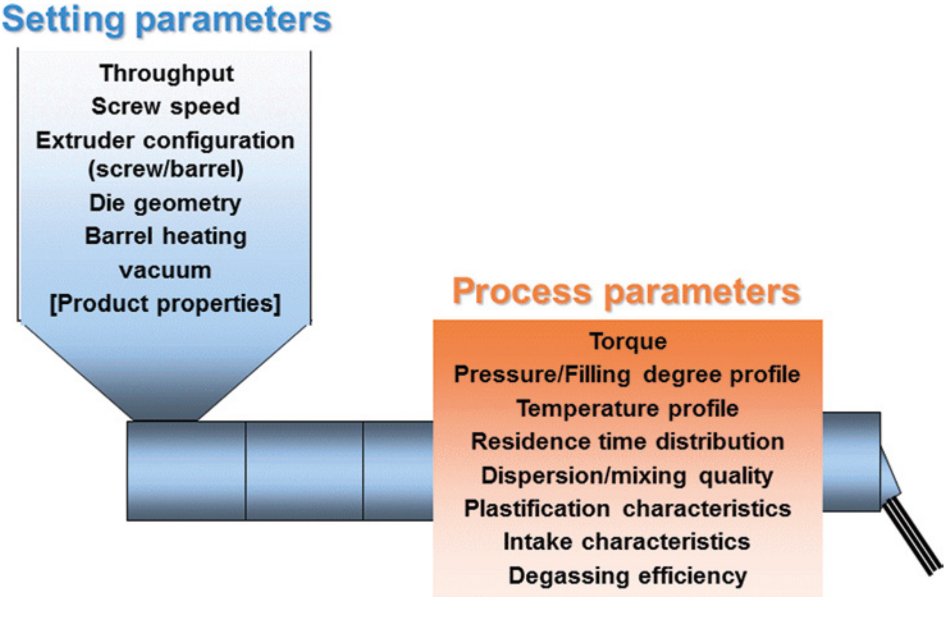


Figure 1.52 Parameters of the compounding process

Depending on the product to be processed and its requirements, the throughput of a compounding process can be limited by the available volume, torque, and/or the maximum tolerable product temperature.

In the following, we will describe each processing zone in a co-rotating twin-screw extruder.

1.3.2.1 Intake Zone

Tasks of the intake zone are:

- Convey and compress solids
- Remove any air that is drawn in

Key setting parameters are:

- Screw speed
- Throughput
- Free screw volume
- Pitch
- Bulk density of the product
- Friction between product and barrel wall

All intake processes are limited by volume [4].

The feed capacity depends on the free screw volume (channel depth, number of threads), the pitch, the screw speed, and the bulk density of the product. The product can only be conveyed if there is friction between the product and the cylinder wall.

Self-wiping screw elements with the maximum possible number of threads give the largest free cross-section (see Figure 1.19 in Section 1.2.2.1.1). Thus, triple-flighted elements should be used in the intake zone of twin-screw extruders with $D_o/D_i < 1.3$, and double-flighted elements in the case of $D_o/D_i > 1.3$. An intake zone length of 4 to 6 D is generally adequate for effective product feed.

The pitch should be 1.5 D directly below the feed hopper. A reduction of the pitch in the feed zone should be avoided to avoid accumulation of the product, as this can lead to a reduction in throughput. At the end of the intake zone, the compression of the solid can cause local pressures of up to 200 bar which, depending on the polymer, may lead to a greater or lesser degree of wear. It is therefore recommended that the elements at the end of the intake zone and at the beginning of the plastification zone are wear protected or have a reduced diameter.

An increase in the free cross-section and hence a 10 to 15% increase in the resulting maximum feed capacity is possible by using (non-self-wiping) pushing flight elements.

When conveying solids with a low bulk density, high fill rates in the intake zone can cause fluidization, if the air that is drawn in cannot escape from the extruder. This can be avoided by a partially filled downstream plastification zone (e. g., with only conveying kneading blocks and no re-conveying elements) and a vent opening installed downstream of the plastification zone.

The product is heated via the barrel wall and heating depends on the available heat exchanger surface and the residence time in the intake zone. Because the surface/volume ratio decreases as the screw diameter increases, product preheating in the intake zone is not relevant in large machines. Effective preheating prior to melting is therefore only possible in large machines before the product is fed into the extruder [5].

The intake barrel is cooled to prevent low melting point components, e. g. waxes, from adhering to the barrel wall or to the feed hopper, because this would severely affect the intake characteristics.

An exact prediction of the conveying behavior or the conveying capacity in the intake zone is currently only possible by means of trials. The knowledge of material characteristics such as bulk density, flowability, and particle size distribution also do not allow a clear conclusion on the feeding behavior. However, conveying of simple, granular materials can already be simulated very well today. It is expected that conveying behavior of mixtures of granules and powders, as they often occur in compounding, can also be sufficiently simulated in the future.

1.3.2.2 Plastification Zone

Tasks of the intake zone are:

- Melting of polymers
- Pre-dispersion of fillers

Key setting parameters are:

- Screw speed
- Throughput
- Screw geometry
- Heat flux
- Specific heat capacity
- Heat conduction
- Melting enthalpy
- Particle size

Comprehensive investigations of the polymer melting process in co-rotating twin-screw extruders by Bastian/Gabor [6] yielded the following results:

- The melting process is influenced to a high degree by screw speed and throughput; in other words, the degree of filling and the residence time

- The required melting length depends substantially on the melting enthalpy of the polymer, the viscosity of the melt, and the screw geometry
- Significant melting starts at the point, where the screw is initially fully filled
- Varying the barrel temperature in the plastification zone makes hardly any difference to the melting process.

Melting can be accelerated by [6]:

- A high degree of filling
- Low melting temperatures
- Small pellet sizes
- A low degree of crystallinity
- Low melting enthalpy
- High melting viscosities
- Low flow activation energies (= temperature influence on viscosity variation)
- Narrow kneading discs

In addition, for polymer blends, the ratio of melt viscosities of the blend partners $r = \eta_{dispers} / \eta_{contin}$ has a major influence on the melting process. In this case, $\eta_{dispers}$ is the viscosity of the blend partner present in the dispersed phase and η_{contin} is the viscosity of the blend partner present in the continuous phase. The smaller the value of r, the sooner the melting process begins, but also the longer it takes [6]. In unfavorable process conditions, as yet unplasticized particles may be encountered in the compounded pellets (see Figure 1.53).

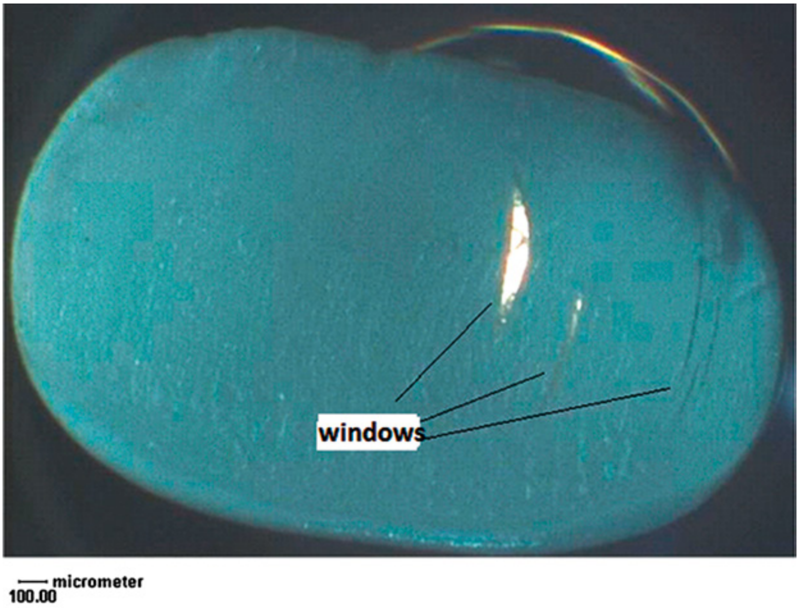


Figure 1.53 Unplasticized particles (so-called windows) within a pellet

The addition of low-viscosity additives can impede the formation of the melt film that is essential for melting. On the other hand, high-viscosity or solid additives can cause increased energy dissipation due to internal and external friction, which accelerates the formation of the melt film but can also lead to overheating of the viscous phase.

Along with the actual melting, part of the key tasks of dispersion and homogenization also takes place in the plastification zone.

Depending on the subsequent process steps, achieving 100% melting at the end of the plastification zone may not be mandatory. Solid particles still present after the plastification zone can be melted in subsequent zones, e.g. in the dispersion or discharge zones. Figure 1.54 illustrates a typical melting profile along a plastification zone.

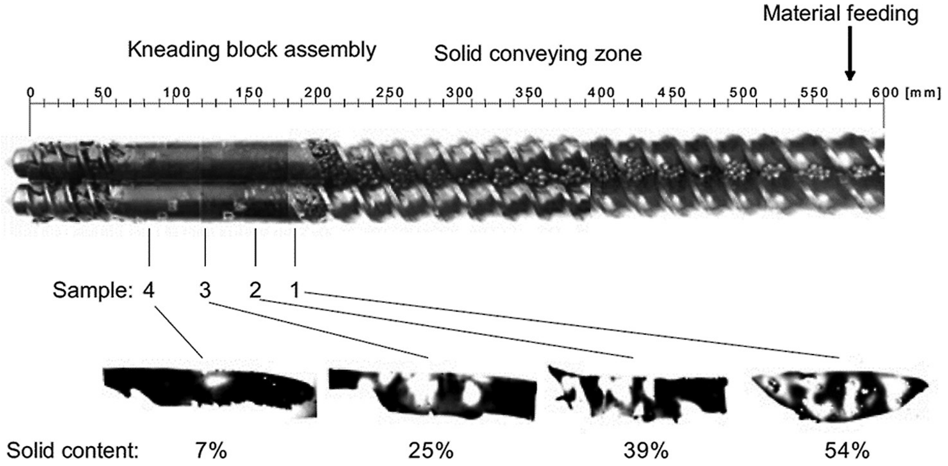


Figure 1.54 Melting profile along a plastification zone [7]

The energy required to melt the polymer components is mainly transmitted via the screw shafts; the heat flow through the barrel wall serves only to form a melt film on the wall [3]. This melt film is important to create an adhesion of the polymer on the wall, thus generating a shear gradient [8]. To achieve this, the temperature of the barrel wall must be higher than the softening point of the polymer.

Up to 80% of the overall mechanical energy input in the twin-screw extruder takes place in the plastification zone. Unfortunately, the calculation of the melting process is currently only rudimentary.

Typically, double- or triple-flighted kneading blocks are used to facilitate melting. The influence of the kneading block geometry on the process parameters is shown using a double-flighted kneading block (see Figure 1.55).

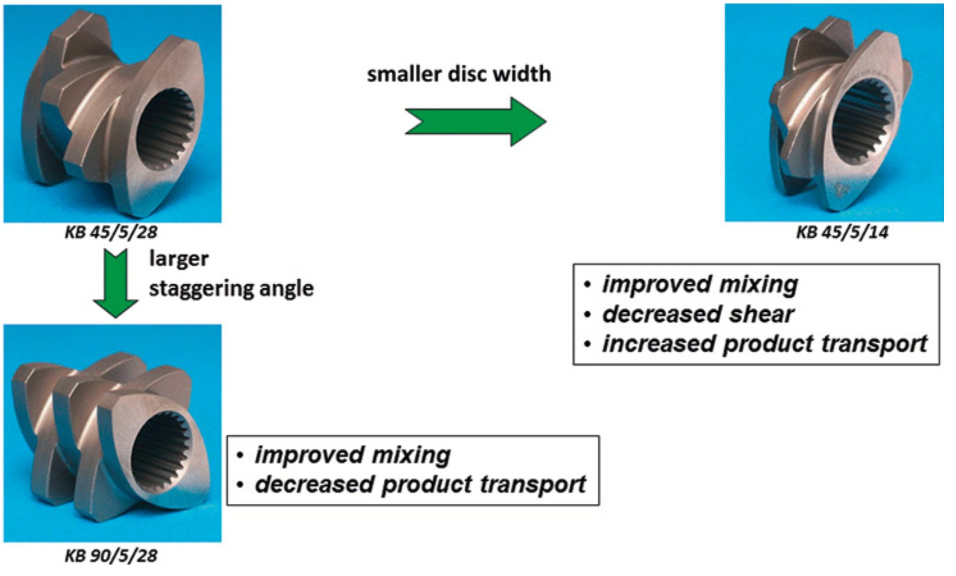


Figure 1.55 Geometric values and process variables of a double-flighted kneading block

A larger staggering angle leads to:

- A reduction of the downstream conveying action of the melt and thus to
- An improved mixing performance because more leakage streams are generated and the residence time increases.

A narrower kneading disc results in:

- Reduced shear in the kneading gap,
- Increased downstream conveying action of the melt, and
- More efficient mixing due to the generation of more leakage streams (see Figure 1.56).

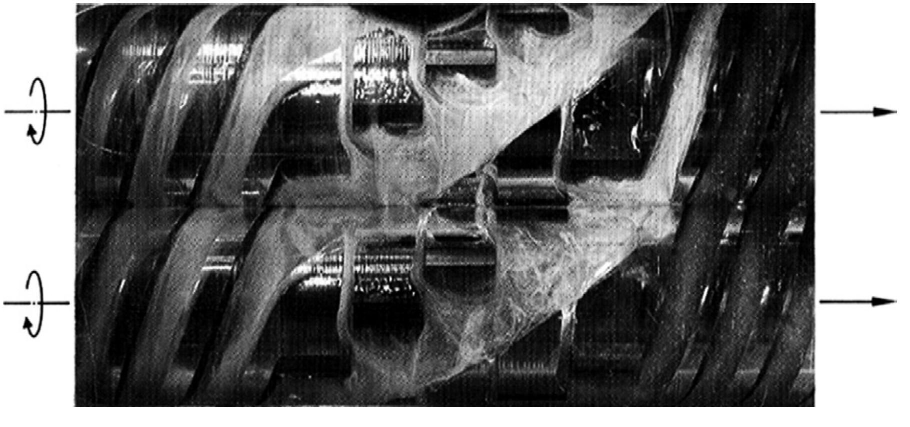


Figure 1.56 Melt streams in a kneading block zone: broad main stream in the feed direction and narrow leakage flow [9]

Melting with triple-flighted kneading blocks results in less energy dissipation compared to double-flighted kneading blocks. However, the melting length required is longer [6].

Melting is accelerated in completely filled zones. It is therefore beneficial to install a re-conveying element at the end of the plastification zone to cause back-pressure in the melt. Kneading blocks (re-conveying or neutral), re-conveying screw elements, or slightly re-conveying mixing elements are generally used for this purpose. However, re-conveying screw elements can cause high pressure and temperature peaks and should be avoided as far as possible (see Chapter 4). For complex melting operations, e. g. with high/low-viscosity multicomponent mixtures, sieve discs can also be used to create back-pressure, provided that the higher energy input generated by these discs is tolerable.

If the feedstock polymer is a fine powder, or if it is necessary to incorporate low bulk-density fillers in large quantities, the plastification zone should be operated partially filled to prevent fluidization in the intake zone. Partial filling can be achieved when the plastification zone only consists of forward pumping kneading blocks and there are no re-conveying elements at the end of the plastification zone. In this case, however, the melting length must be considerably longer.

Melting in a fast-running, high-performance extruder can result in temperature peaks if conventional kneading blocks are used. These peaks can damage the polymer. To prevent these temperature peaks, less closely intermeshing screw elements have been developed. They reduce the shear peaks to provide a gentler compounding action. Examples include Multi-Process Elements (MPE) (Berstorff), triple-flighted eccentric kneading blocks with reduced external diameters, and shoulder-type kneading blocks (e. g., Extricom, Coperion). Scheel has shown, for example, that it is possible to achieve melting of polyamides with an MPE plastification zone with 10% lower energy input than with a conventional kneading block plastification zone (see Figure 1.57) [10]. This means a reduced melt temperature with the same throughput and/or a higher throughput at the same melt temperature.

The energy input via the screw elements and kneading discs results in splaying forces, particularly in the plastification zone, which can cause wear to the cylinders (see Figure 1.58). This can be reduced by an appropriate design of the plastification zone and by heating the cylinder wall, which results in the formation of a melt film [5].

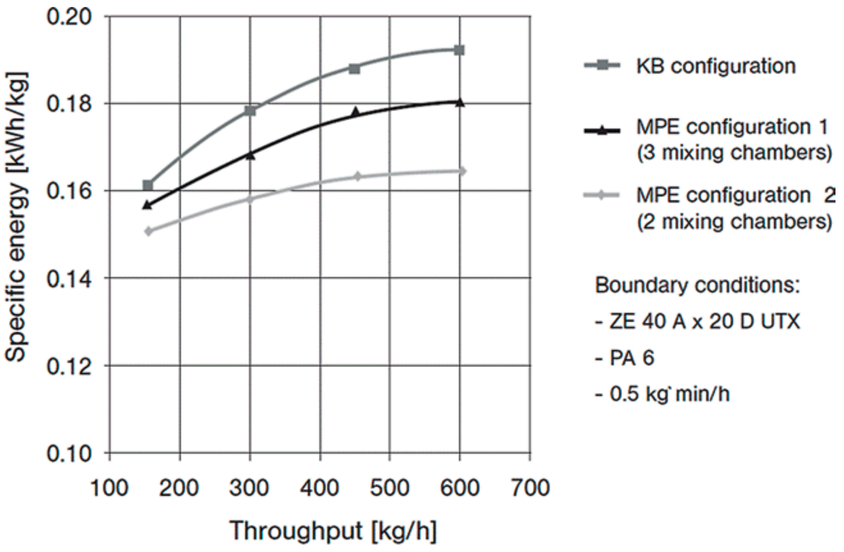


Figure 1.57 Energy input as a function of throughput for polyamide melting with kneading block and MPE plastification zones [10]

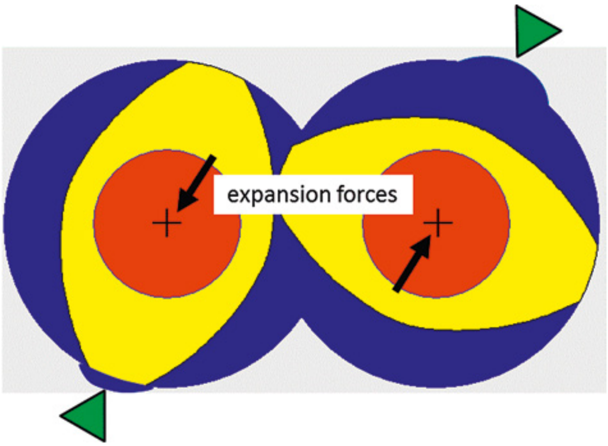


Figure 1.58 Cylinder wear caused by expansion forces [5]

1.3.2.3 Melt Conveying Zone

Tasks of the melt conveying zone are:

- Convey melt

Key setting parameters are:

- Screw speed
- Throughput

- Pitch
- Material properties

Melt conveying zones are generally partially filled, except for the back-pressure zones upstream of pressure consuming elements.

Figure 1.59 shows an example of the filling degree as a function of the pitch at two different screw speeds (400 rpm and 600 rpm) and a constant throughput of 2500 kg/h for a twin-screw extruder ZSK 92 Megacompounder with 92 mm outer screw diameter.

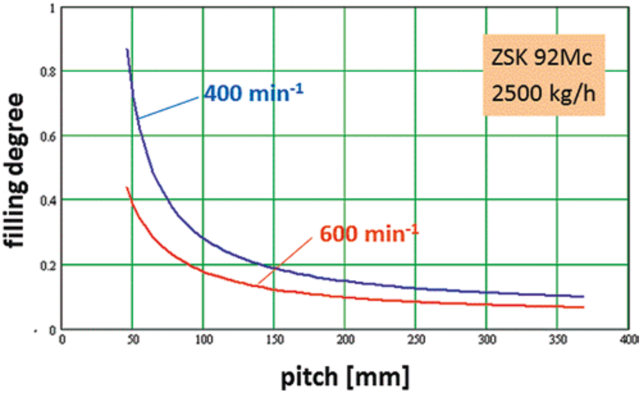


Figure 1.59
Filling degree as function of pitch and screw speed

The melt conveying zones serve to transport the product from one process zone to the next and to feed fillers. Leakage flows over the screw tip and in the intermeshing zone also cause some slight back-mixing. As little energy as possible should be dissipated in the melt conveying zones.

For simple melt conveying, screw elements with a pitch of 1 *D* are commonly used. If other components are to be added (e.g., via a side feeder), the pitch should be 1.5 *D* to increase the feed capacity.

As will be shown in subsequent chapters, melt conveying can be calculated very well provided that sufficient material data is available.

1.3.2.4 Distributive Mixing Zone

Tasks of the distributive mixing zone are:

- Distribution of solids or fluids in the melt
- Homogenization of the melt temperature

Key setting parameters are:

- Screw speed
- Throughput
- Screw geometry

The aim of the mixing process is to achieve homogeneous distribution of solids or liquids within the melt with the shortest mixing lengths and minimum energy input.

Due to the laminar flow of polymer melts in an extruder, mixing is entirely the result of kinematic distributing processes related to the extruder operating characteristics. This can be described in terms of the ratio of drag and pressure flows. The actual homogenization process (distribution process) depends entirely on the intensity and direction of these flow portions and not on the viscosity of the melt.

The mixing performance depends significantly on the dimensionless kinematic parameter of flow $\Lambda = \frac{1}{A_1} \cdot \frac{\dot{V}}{n \cdot D^3}$ (Figure 1.60). A_1 indicates the maximum throughput of the screw element per revolution that the machine can achieve when it is completely filled and operated without back-pressure (known as inherent throughput, see Section 4.1 for a more detailed description of the dimensionless representation). $\dot{V}$ represents the volumetric flow rate, n is the screw speed, and D the barrel diameter. Figure 1.60 shows the mixing quality as a function of Λ for silicone oil with Newtonian viscosity behavior into which iron powder has been mixed [11]. In principle, this behavior also applies to shear thinning materials.

The higher the screw speed and/or the lower the throughput, the better is the mixing performance. The figure also shows that re-conveying elements (Λ < 0) provide significantly better mixing performance than conveying elements (Λ > 0).

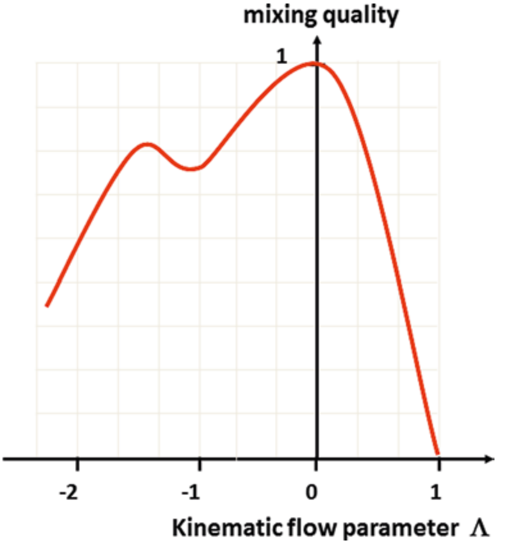


Figure 1.60 Influence of the kinematic parameter of flow Λ on the mixing quality [11]

Mixing is improved when the melt streams are subjected to displacement in addition to shear deformation. Special mixing elements have been designed for this purpose, e.g. toothed blocks or toothed mixing elements. Kneading blocks with narrow discs also provide a better mixing performance than screw elements (advantages compared to broad discs: better mixing performance because the greater number of discs per length results in more melt stream splitting; less shear due to less wedge flow between screw flank and barrel see also Figure 1.56). Mixing/homogenization ideally takes place in melt-filled zones.

If a large quantity of a low-density powdered component is to be incorporated, the air that is drawn in with the powder must be removed to prevent fluidization. In principle, there are three methods to achieve this:

1. Partially filled mixing zone with conveying kneading blocks so that the air can escape in the direction of flow through a downstream vent opening.
2. Feeding of the powder at two or more positions in the extruder (e.g., one at the first intake and the rest via a side feeder).
3. Use of pre-compacted powder to reduce the amount of air drawn in.

1.3.2.5 Dispersive Mixing Zone

Tasks of the dispersive mixing zone are:

- Breaking down solids, polymer particles, and fluid droplets

Key setting parameters are:

- Screw speed
- Throughput
- Screw geometry
- Viscosity

Like the degree of distribution, the degree of dispersion is dependent on the kinematic parameter of flow Λ. However, along with the axial and radial velocities in the screw channel, the dispersion process is also dependent on viscosity and is therefore affected by the shear stresses in the screw channel (Figure 1.61). The figure shows the dispersion degree of TiO_2 agglomerates as a function of Λ for silicone oils of differing viscosities for an isothermally-operated single-screw extruder [12]. In principle, the same applies to twin-screw extruders.

The dispersion effect is dependent on the shear stress as well as on the duration of the load. Which of the two parameters has the biggest influence depends on the material to be dispersed [13]. On the basis of tests on a single-screw extruder, Martin has demonstrated that the dispersion of carbon black agglomerates is only possible by exceeding a minimum shear stress and a minimum load time [14] (Figure 1.62). According to Potente, there is also a maximum shear stress above which an agglomerate spontaneously breaks down [18].

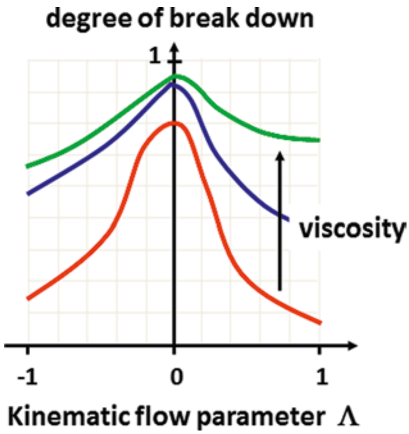


Figure 1.61 Influence of kinematic parameter of flow Λ and viscosity on the dispersion degree of TiO_2 agglomerates in silicone oil (trials with a single-screw extruder) [12]

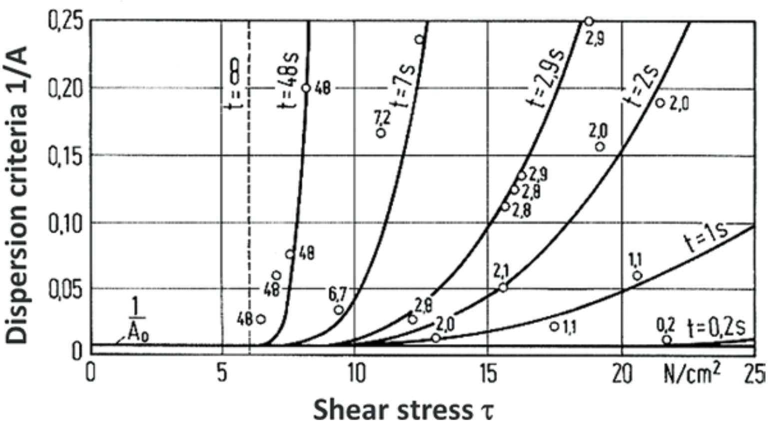


Figure 1.62 Dispersion rate of carbon black agglomerates in a PE melt depending on the shear stress and stress duration (trials with a single-screw extruder) [14]

Together with a sufficient residence time in the shear zone, effective dispersion is also encouraged by

- High screw speed
- Low throughput
- Narrow shear gaps
- High melt viscosity

Wide-disc kneading blocks achieve the most effective dispersion because they generate the highest shear stresses. This also leads to high energy input, however, which increases the melt temperature and reduces the viscosity of the predominantly shear-thinning polymer melts, which in turn leads to a reduction of shear stress. Therefore, dispersive mixing is an optimization problem.

The purely mechanical dispersion of the agglomerates can be assisted by the addition of dispersion aids (e. g., amide, polypropylene, or polyethylene waxes; metal carboxylates; organic fatty acids and their esters), which wet the particle surfaces, thus reducing the interaction between them (Figure 1.63) [16]. This significantly lowers the shear stresses required to disperse the agglomerates.

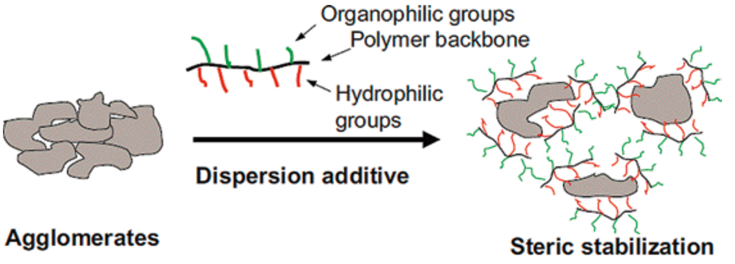


Figure 1.63 Effect of dispersion additives

1.3.2.6 Devolatilization Zone

Tasks of the devolatilization zone are:

- Removal of water, residual monomers, and solvents

Key setting parameters are:

- Screw speed
- Throughput
- Available screw volume
- Vacuum

Due to the axially open screw channels in the co-rotating twin-screw extruder, the devolatilization zone must be sealed by completely filled zones on either side of the devolatilization opening to prevent, for example, extraction of components that have not yet been incorporated from upstream or downstream zones. Re-conveying or neutral kneading blocks neutral re-conveying or mixing elements are used to achieve the melt-filled zones. Generally, screw elements with 1.5 *D* pitches are used in the devolatilization zone itself. These are operated partially filled to provide as large a product surface as possible for devolatilization and also to prevent product from discharging into the vent.

The best devolatilization efficiency can be achieved with

- High melt temperature
  - Low equilibrium concentration, high diffusion constant
- Low degree of filling caused by a large available screw volume (large channel

depth, large number of threads, long zone) and a low throughput/screw speed ratio
  - Large devolatilization surface
- High screw speed
  - Frequent surface renewal
- Addition of entraining agent
  - Low partial pressure
- High vacuum
  - Low equilibrium concentration.

The vent opening should be as large as possible to avoid high gas speeds, which can lead to product being drawn into the vent.

In practice, three vent inserts are used to ensure effective devolatilization on the one hand and to prevent product from discharging into the vent on the other hand (Figure 1.64):

- Form A: for polymer melts that do not adhere to the screw (e. g., PVC, polyolefins)
- Form B: for polymer melts that adhere to the screw (e. g., PA, PET, PC)
- Form C: for large volumes of gas in polymer melts that adhere to the screw (e. g., PA, PET, PC)

Alternatively, vents with vent stuffers can be used to prevent product discharging. However, this will reduce the devolatilization efficiency due to the reduction of the available devolatilization cross-section.

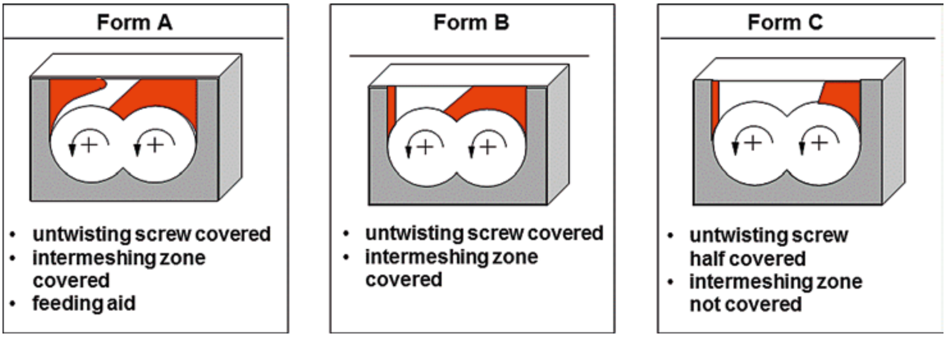


Figure 1.64 Vent inserts (according to Coperion [13])

1.3.2.7 Pressure Build-Up Zone

Tasks of the pressure build-up zone are:

- Build up pressure

Key setting parameters are:

- Screw speed
- Throughput
- Pitch
- Gap between screw and barrel

Pressure build-up zones are located in the extruder in the discharge zone and upstream of each backward conveying screw element, e. g. mixing elements, re-conveying, or neutral kneading blocks.

The pressure required to overcome the backward conveying elements has to be generated in the pressure build-up zones. The pressure consumed by the tool and any subsequent units (e. g., melt filters) has to be generated in the discharge zone. There is a greater reflux of melt over the screw tips in the pressure build-up zone resulting in more intense melt mixing.

Today, the pressure build-up zone can be calculated with sufficient accuracy provided that adequate material data are available. The aim of the design is generally to generate the required pressure consuming as little energy as possible. Figure 1.65 shows the energy input in the melt-filled pressure build-up zone on the basis of preset values for pressure build-up, throughput, and screw speed. The energy inputs are compared for single-flighted and double-flighted ($Z = 1$ or 2) conveying elements with different pitches T (as multiple of barrel diameter D) and screw/barrel clearances (δ). The end of the pressure build-up length is characterized by the end of the curve. It is apparent that with single-flighted conveying elements the required pressure can be generated with considerably less energy input and a shorter pressure build-up length. However, it should be noted that single-flighted conveying elements have a tendency to pulsate, because there is only one product flow in comparison to three product flows in the case of double-flighted elements. Metering fluctuations can therefore more rapidly lead to throughput fluctuations than in the case of double- or triple-flighted elements.

For the same example, Figure 1.66 shows that pressure build-up ability and energy input depend not only on screw geometry but also on the process parameters (in this case: screw speed), i. e., in the end on the kinematic parameter of flow Λ. For a pitch of $T = 0.3\,D$, the energy input decreases and the pressure build-up length increases as the screw speed decreases. For a pitch of $T = 0.2\,D$, however, the energy input increases as the screw speed decreases. Pressure build-up is no longer possible above $n = 145$ rpm at a throughput of 100 kg/h, because Λ is greater than 1 (see also Section 4.2).

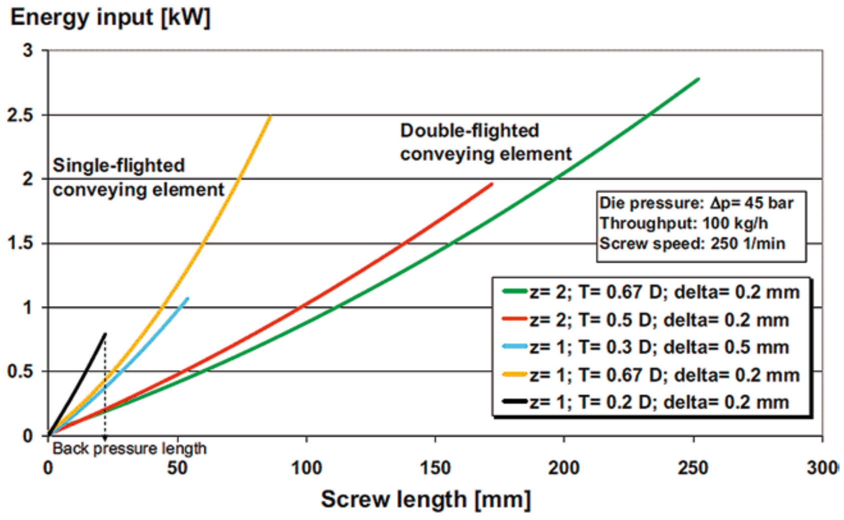


Figure 1.65 Energy input in the pressure build-up zone for different conveying elements

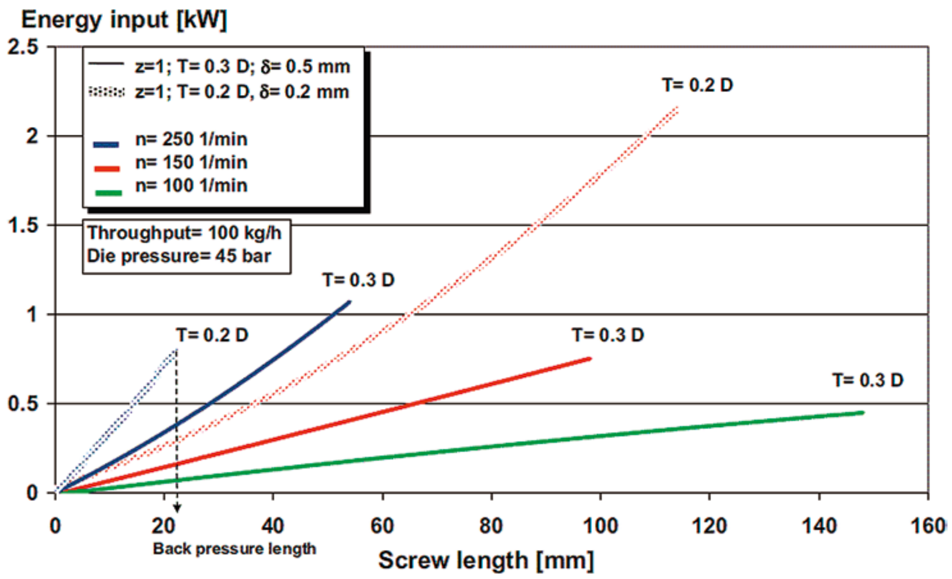


Figure 1.66 Influence of screw speed and pitch on the energy input in the pressure build-up zone

To prevent excessive energy input in the discharge zone, pressure build-up for very high pressures and/or temperature-sensitive polymers can also be generated by a downstream gear pump that has a considerably greater pumping efficiency than the co-rotating twin-screw extruder (see Figure 1.67 and Section 4.3.2).