New Concepts for Extrusion Screws

On the Wave to Successful Mixing

On the test stand: the University of Paderborn, Germany, investigated conventional and new concepts for extrusion screws in order to achieve higher throughputs while retaining machine sizes. The energy-transfer screws, a further development of the wave screw, scored particularly well.

Extrusion lines have to work economically. The efficiency of single-screw extruders in particular was improved by increasing throughput while retaining machine sizes. Supplementary to conventional screws, new screw concepts were developed to ensure high melt quality. These belong to the so-called wave screws that break up the solid bed at an early stage, thereby optimizing melting and homogenizing behavior.

Twin-flight double-wave and energy-transfer screws are the most widespread wave screws and are characterized by periodically rising and falling channel depths. The resulting waves are staggered so that one channel has a trough while the other channel has a crest, and vice-versa. As with barrier screws, the twin channels of the double-wave screws (DW screw) [1] are separated by a constantly offset secondary flight whose gap to the barrel is wider than that of the main flight. As a result, mixing is greatly promoted by splitting the melt at a wave crest via the secondary flight and via the wave crest itself, thereby promoting higher thermal and material homogeneity. The design of an energy-transfer screw (ET screw) [2] is similar to that of a double-wave screw. However, the main and secondary flights are separated in such a way that the melt can flow over the flight at the respective wave crest into the upstream screw channel (**Fig. 1**). The function of the main and secondary flights alternates in such a way that the melt repeatedly changes the channel counter to the direction of flow, thereby further increasing the mixing effect.

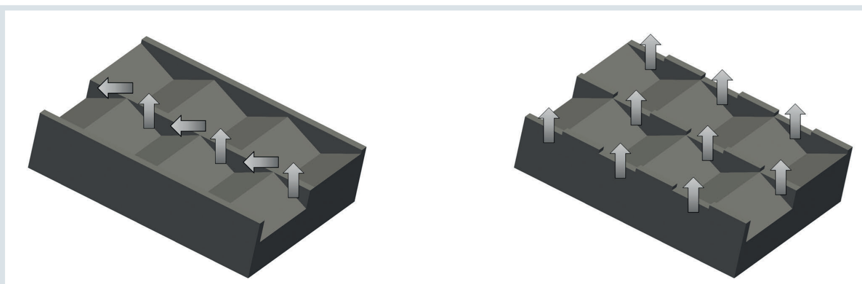

Fig. 1. Unwound channel geometry of a double-wave (left) and an energy-transfer screw (right).

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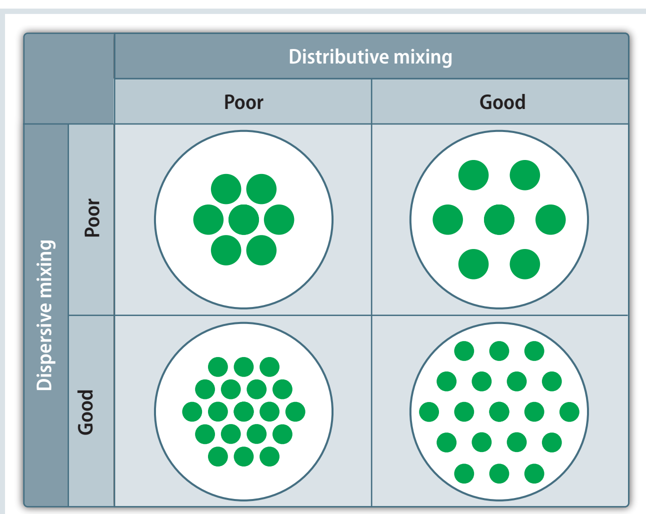

Fig. 2. Schematic representation of the dispersive and distributive mixing mechanisms.

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Mixing Sequences in Single-Screw Extrusion

Besides plasticizing and conveying the melt, mixing is one of the main tasks of the screw in single-screw extruders. The product quality of the extrudate corresponds directly to the homogeneity of the melt. For economic reasons, an additional compounding step is being eliminated more and more often, in consequence of which a single-screw extruder has to perform increasingly difficult mixing tasks [3].

The mixing sequences taking place in single-screw extruders are fundamentally divided into the two basic types of mechanism shown in **Figure 2** [4]. The one is dispersive mixing, which wets solid materials in the form of agglomerates and aggregates with the polymer melt and breaks them up into the smallest possible primary particles in shearing and stretching sequences. The other, distributive mixing, was focused on by the following investigations. It distributes the melt particles as homogeneously as possible by deforming and redistributing them.

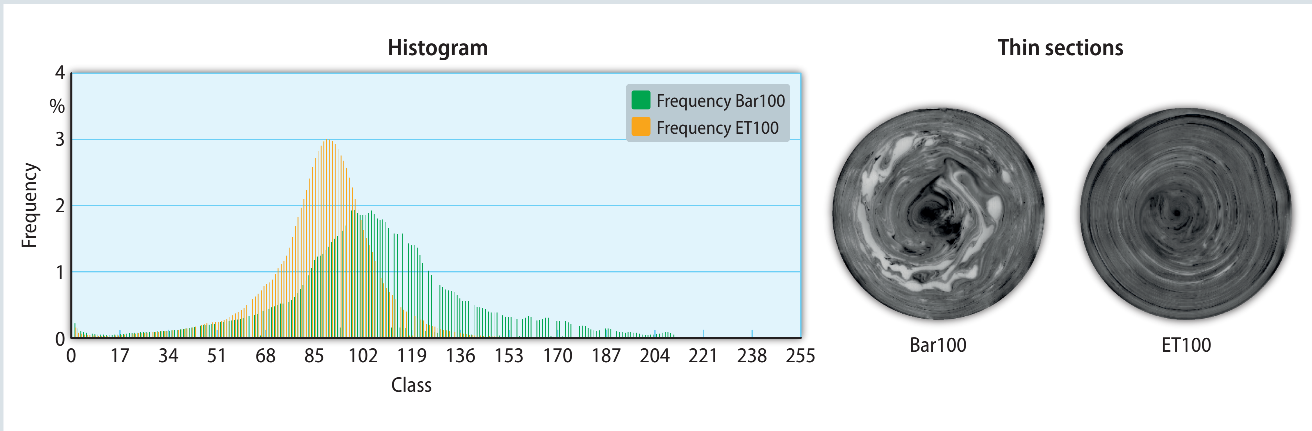

Fig. 3. Exemplary estimate of gray value distribution as a histogram (left) with thin sections belonging to barrier and energy-transfer screws at 100 rpm. Source: Paderborn University, graphic: © Hanser

Mixing Quality under the Microscope

In order to evaluate distributive mixing quality, both experimental and simulative investigations were performed on four different screw concepts and compared correspondingly. To this end, a classic three-section screw, a classic barrier screw, as well as a double-wave and an energy-transfer screw were employed. None of the screws had any additional mixing and shearing equipment.

Material homogeneity was analyzed experimentally on the basis of three thin sections taken from a sample strand with a material mixture of HDPE with 0.2 % black masterbatch. The samples were subsequently scanned, and the individual pixels converted into a gray value distribution. As shown in **Figure 3**, histograms result whose frequency distributions of the respective pixel frequencies lie within a scale from 0 (pure black) to 255 (pure white). The histograms were subsequently evaluated according to their statistical parameters in order to characterize the width and shift of the color range and black intensity. The mixing ratio here always lies between 100 % (best mix) and 0 % (worst mix).

For the simulative investigations, each screw was simulated in its entirety. To do so, the melting behavior sketched exemplary in **Figure 4** was performed using a single-component 2-phase CFD simulation which models the solid material versus the melt as a very highly viscous fluid. Using a transition function, both the solid and the melt can be assigned their respective material properties.

To characterize the distributive mixing quality, a particle cloud with several particles was defined in the solid bed and the trajectories calculated along the screw accordingly (**Fig. 5**). Based on the two-dimensional particle distribution at the outlet, the screw can then be characterized in terms of its mixing quality.

There are already various procedures for this, but they are associated with various disadvantages. One example worth mentioning is the so-called "bin counting". The flow is divided into equal cells called bins, and the uniformity of the particles distributed in the bins is characterized according to their variance. As an example, various distributions are shown schematically in **Figure 6**. However, the procedure mentioned exhibits serious disadvantages in several aspects. For one thing, various geometry sizes, cross-sections, or channel depths cannot be compared with each other. Moreover, complex geometries, as in the case of a screw cross-section with flight, are insufficiently separated into uniform bins. **Figure 6** shows this very clearly. Both distributions in the middle zone show the same homogeneity value, although the particle distributions exhibit no similarity at all. Furthermore, the result is strongly influenced by the number of bins, as well as by the number of particles which are subject to frequent fluctuations due to various residence times and numerical instabilities. »

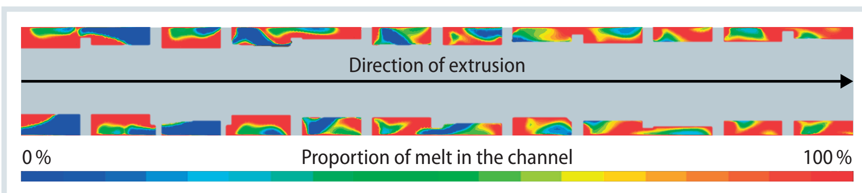

Fig. 4. Channel cut of the simulation in the melting zone of the screw. Source: Paderborn University, graphic: © Hanser

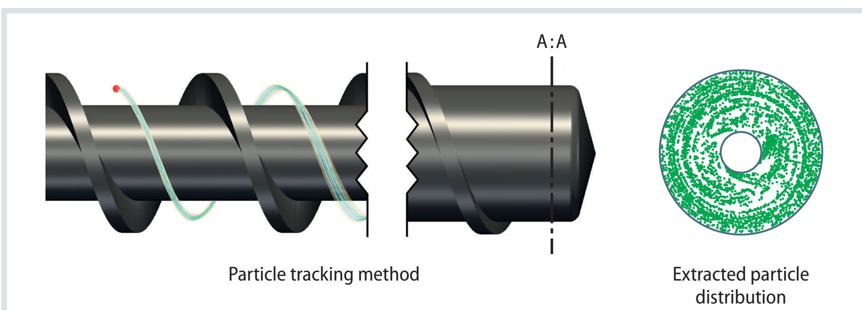

Fig. 5. Scheme of the particle tracking method as well as extracted and triangulated particle distribution. Source: Paderborn University, graphic: © Hanser

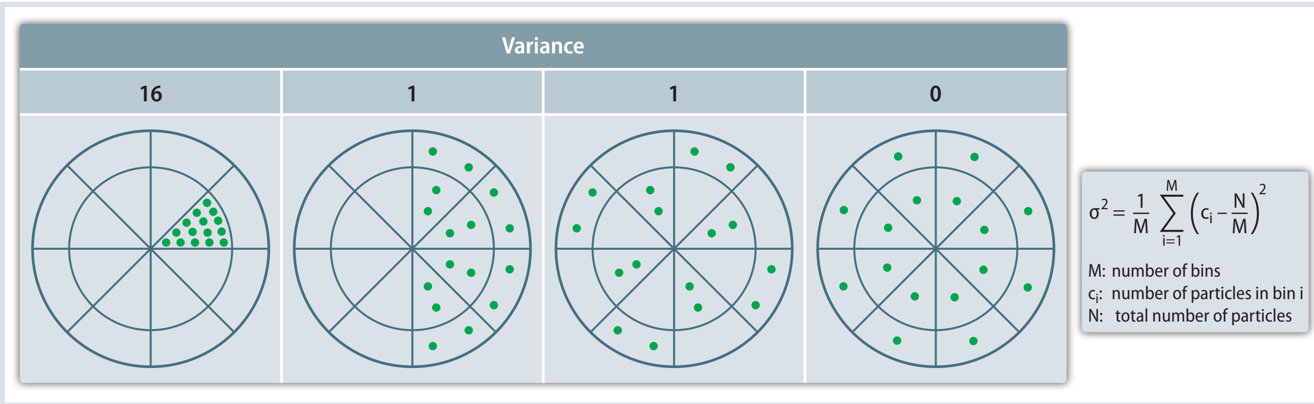

Fig. 6. Exemplary application of the bin counting method. Source: Paderborn University, graphic: © Hanser

Based on this fact, a novel method was selected on the basis of Delaunay triangulation. As shown in **Figure 7**, a triangular mesh is spanned out of the 2D particle distribution. The Delaunay triangulation is a special case which achieves maximized interior angles due to compliance with the so-called circumcircle condition. As can be seen in **Figure 7**, the circumcircle condition serves to prevent any additional point from being included within the circumcircle of a triangle [4]. The spanned triangle is evaluated on the basis of standard deviation and average value under the assumption that a homogeneous particle distribution is also associated with triangles that are homogeneous in terms of area. The advantage of this method for mixing quality is expressed, for example, by the independence of the characteristic value of the number of particles. This is especially important, since different particle numbers at the flow outlet occur due to numerical instabilities and different residence times. Moreover, the method features high flexibility, since it can analyze any cross-section. In contrast to bin counting, the new method can evaluate mixing quality even in areas where there are flights. It is also possible to scale up or down, since the evaluation can be done independently of cross-section size. The

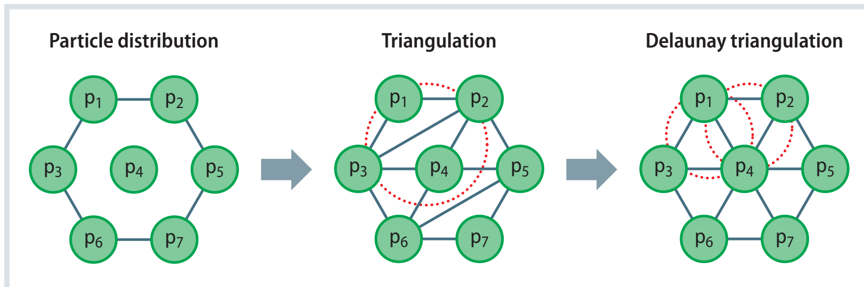

Fig. 7. Exemplary triangulation of point distribution by Delaunay triangulation.
Source: Paderborn University, graphic: © Hanser

experimental investigations were performed on a Battenfeld BEX 1–45–30B smooth barrel extruder with D = 45 that can be operated up to a maximum of 585 rpm. The speeds investigated for determining throughput ranged from 50 to 500 rpm. For the barrier as well as the 3-zone screws, however, the high speeds could not always be achieved due to insufficient melting power. A throttle die was used. The exemplary material used was a HDPE (HE3493-LS-H) from Borealis. The temperature curve used corresponded to the suggestion of the materials manufacturer.

The Throughputs of the Different Screw Concepts

There are great differences in the maximum throughputs achievable with the different screw concepts (**Table 1**). The wave screws exhibit notably higher achievable throughput with high melt quality due to the higher mixing quality as well as to the higher energy input from repetitive shearing over the secondary flight. The energy-transfer screw achieves up to 98.4 kg/min throughputs, 57 % higher than with the barrier screw. For the homogeneity investigations, two speeds (100 rpm and 200 rpm) were used with each screw concept. **Figure 8** shows a comparison of the material homogeneity of experimentally determined thin sections as well the evaluated particle distributions of the different screw concepts at 100 rpm. Clear differences can be perceived. With the three-section and barrier screws, larger areas with continuous white portions can be seen. This contrasts with clearly fewer border surfaces visible between the white and

Table 1. Comparison of the throughputs of HDPE achieved by the different screw concepts given completely melted polymer flow.
Source: Paderborn University

	Three-section screw	Barrier screw	Double-wave screw	Energy-transfer screw
Throughput [kg/h]	42.2	62.8	85.1	98.4

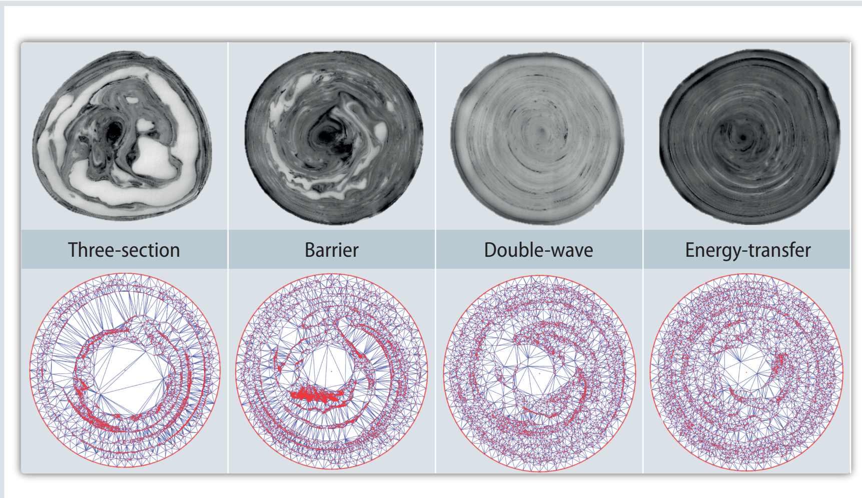

Fig. 8. Qualitative comparison between the experimentally determined thin sections at the end of the screw and the triangulated, simulatively determined particle distributions at 100 rpm. Source: Paderborn University, graphic: © Hanser

estimate of real mixing quality can be represented by using innovative simulations, and that this can be used for the most economical design possible. Elaborate experimental investigations can then be substituted by faster, more economical, and clearly more variable simulative tests of screw geometries. This would enable optimum configuration of screw concepts for a wide range of applications. ■

black segments so that the extruded melt strand is considerably more homogeneous. It can also be observed that the larger collections of areas with white zones are visibly reflected in the simulatively determined distributions in the form of large areas with collections of particles.

Clear correspondences can be seen in **Figure 9** when we compare the quantitative, statistically determined characteristic values of the simulatively and experimentally determined mixing qualities. The three-section screw exhibits the poorest mix. Moreover, testing was possible only at 100 rpm, since the melt was no longer sufficiently mixed and melted at 200 rpm. Compared to the three-section and barrier screws, both innovative wave screw concepts exhibit clear advantages in terms of material mixing quality. Furthermore, a trend can be seen toward a worsening of the mixing for all screw concepts when speed is increased both simulatively as well as experimentally. The consideration of the qualitative and quantitative results shows that the overall best mixing effect is achieved by the energy-transfer screws. The improved return flow over the offset flight into the opposite channel could provide a plausible explanation for this.

The Wave-Screw: High Mixing Quality and Large Degree of Freedom

In conclusion, it can be said that the innovative wave screws can lead to improved melting power and mixing quality accompanied by increased throughputs. It is, therefore, of great importance that they be correctly designed, since they offer more freedom to configure the waves than do the three-section screws, for example. Moreover, in the course of the investigations, it became clear that a plausible

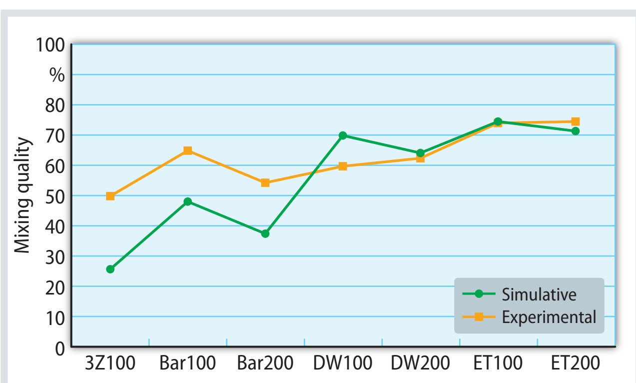

Fig. 9. Comparison of the simulative and experimental results of distributive mixing qualities obtained with different screw concepts at various rpms. Source: Paderborn University, graphic: © Hanser

Info

Text

Maximilan Frank, M.Sc., has been a scientific assistant in Kunststofftechnik Paderborn (KTP) at Paderborn University, Germany, since 2018.
Marius Dörner, M.Sc., is a project leader for Ianus Simulation GmbH.
Dr. Christian Marschik is Area Manager for Process Digitalization at Competence Center Chase GmbH.
Christoph Schall, M.Sc., has been a scientific assistant in Kunststofftechnik Paderborn (KTP) at Paderborn University since 2019
Prof. Dr.-Ing. Volker Schöppner has held the Chair for Plastics Processing at Paderborn University since 2007

Acknowledgments

The authors would like to thank the German Research Foundation (DFG) for funding this project under reference number SCHO 551/41–1.

References & Digital Version

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