Making Mixing Transparent

Experimental Determination of the Flow Processes at Kneading Elements

Variations on the kneading elements of co-rotating twin-screw extruder were produced by an additive manufacturing process with the aim of increasing the processing engineering efficiency. A transparent barrel permits computer-aided quantification of the flow processes, allowing element-specific properties to be analyzed.

The co-rotating, closely intermeshing twin-screw extruder has a particular importance in the compounding of polymers with additives. To obtain optimum mixing results with the least possible costs (high throughput, low energy input), the machine is optimized down to the individual mixing element. It is illustrated below how the dispersive mixing behavior of kneading elements is improved by increasing the stretching flow components while simultaneously reducing the shear loading.

Theoretical Consideration

The shear rate of a fluid moving in the x-direction is defined as:

$$\dot{\gamma}_x = \frac{dv_x}{dy}.$$

In the case of simple plate flow, a Newtonian fluid can be assumed to have a linear velocity profile (**Fig. 1**).

In the co-rotating twin-screw extruder, the biggest shear rates occur at two places: first in the shear gap between the rotating crest and the stationary interior wall of the barrel, and in the nip between the two rotating kneading elements. These shear rates are of the order of several thousand reciprocal seconds [1, p. 42].

The stretching rate of a fluid is defined as:

$$\dot{\varepsilon}_x = \frac{dv_x}{dx}.$$

Consequently, each velocity increase along the flow path has a stretching effect on the fluid. **Figure 2** illustrates such a velocity increase along the flow path.

Stretching flow occurs wherever the flow cross-sections are constricted. In order that an incompressible fluid volume (here, the polymer melt is considered as incompressible for the sake of simplification) can flow through a convergent cross-section, a velocity increase along the path is necessary. The continuity equation applies. For example high stretching rates occur when the fluid passes through the closing nip as well as when it enters the crest gap. In the case of kneading elements, there is no clear separation between the aforementioned flow forms. The shearing and stretching flows are superimposed [2, p. 2.18].

Profile Variation

With a new design method, the angle between the flank of the kneading element profile and the housing can be modified as required. Furthermore, it is possible to reduce the width of the crest. As a result, the shear gap length and the shearing loading of the fluid become smaller. It is important that with this design method, the elements remain closely intermeshing despite the wide variety of shapes.

In the experiments presented here, the traditional double flighted kneading element geometry according to Erdmenger (**Fig. 3**) was modified. In the variants, two of the four flanks – located diagonally opposite one another – were modified. These changes are rather minor compared to the possibilities for

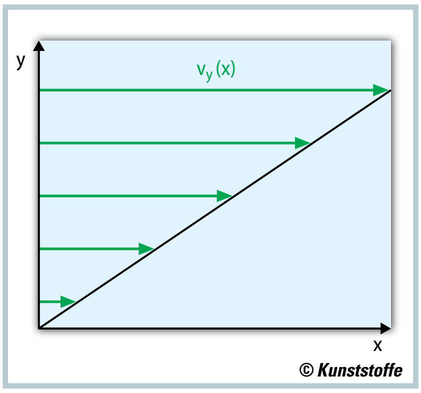

Fig. 1. Schematic view of a shearing flow

(figures: IKT)

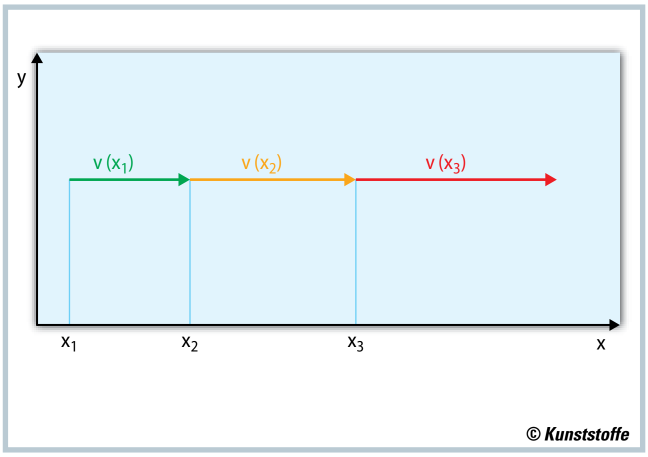

Fig. 2. Schematic view of a stretching flow

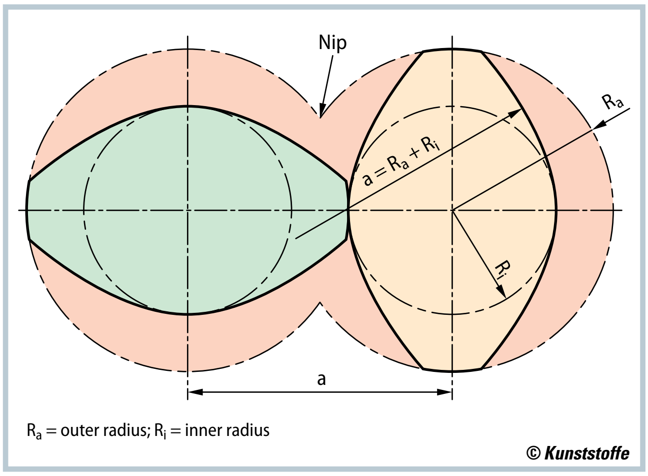

Fig. 3. Double flighted Erdmenger profile

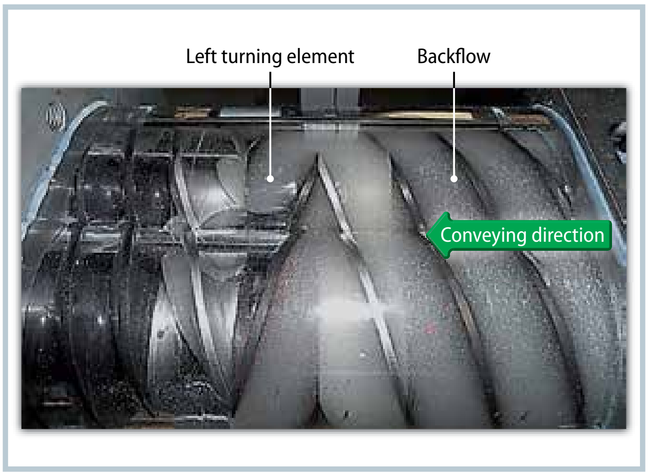

Fig. 4. Backflow front of a left element in the ZSK58 with transparent barrel

geometrical variation. The Erdmenger geometry serves as a reference for the series of trials.

The prototype elements can be produced particularly rapidly and inexpensively using "fused deposition modeling". This is an additive manufacturing process, in which the workpiece is produced layer-by-layer from a meltable polymer (ABS in this case).

Transparent Housing Makes the Fluid Motion Visible

The experiments were carried out using a model fluid on a twin-screw extruder (type: ZSK58, manufacturer: Coperion GmbH, Stuttgart, Germany), in which a part of the barrel is transparent (**Fig. 4**). The model fluid is a thickened glycerine, with discrete polyethylene particles as markers.

The transparent barrel permits the fluid movement in the process part to be recorded, evaluated quantitatively and displayed by means of a high-speed camera (300 images/s). The flow is evaluated at speeds between 50 rpm and 120 rpm. The twin-screw extruder is operated in both completely filled and partly filled mode. As shown in **Figure 5**, the width of the monitoring area is restricted to the distance a between the screw shaft axes. As light source, LED strips are used, which frame the monitoring area and thereby avoid stray light effects.

As an experimental method for visualizing the flow, a 2-D particle tracking velocimetry (PTV) is chosen. The third dimension is approximated towards the housing. To keep the viscosity of the fluid constant in the region of 40 Pa s, it »

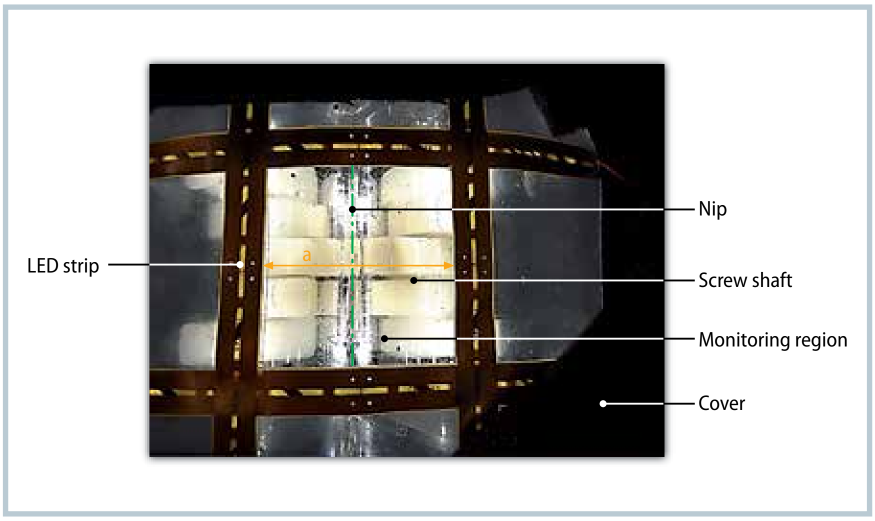

Fig. 5. Observed screw section with lighting and cover

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References & Digital Version

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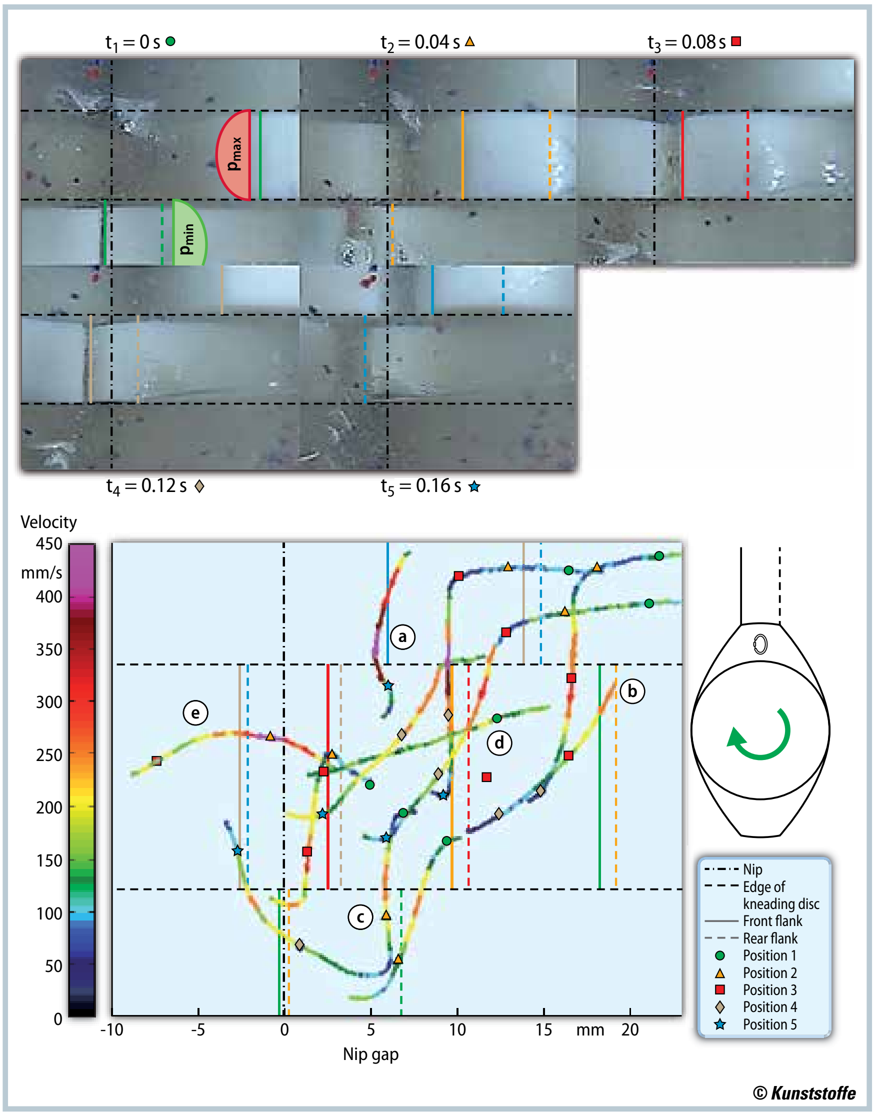

Fig. 6. Flow processes at an individual standard kneading disc

is necessary to adjust the temperature control.

The recorded videos are analyzed into individual images and processed corresponding to the requirements of the Image J tracking software. Tracking the individual particles through the image stack provides the direction and magnitude of the velocity vectors in the non-stationary flow field. The data of the vectors are visualized with the aid of the Matlab software. This allows to determine results that lead to a better understanding of the transport processes at the analyzed flanks, and the resulting properties. Besides the analysis of multiple kneading elements (monitoring range in **Fig. 5**), detailed observations of the flow processes at an individual kneading element, in particular, permit more advanced statements.

Quantification of the Flow Processes

Figure 6 shows this detailed consideration with the example of a conventional geometry according to Erdmenger at a speed of 75 rpm. The conveying direction is from the bottom upwards, with a left element at the top edge of the image. Only the rotating shaft is shown and the direction of view is onto the shaft from above. This rotates from right to left, as can be seen from the original image. The leading edge of a crest of a kneading disc is represented with a continuous line, while the trailing edge is represented by a broken line.

Various colors of marking points show the particle position at defined screw positions. If the color of a marker corresponds to that of a crest line, the same point in time is represented. There is a period of 40 ms between the individual positions. Comparable trajectories are grouped together, with the following subdivision (the grouping relates to the central kneading disc):

a) Particles enter the kneading disc region well behind the crest.
b) Particles enter the kneading disc region close behind the crest.
c) Particles exit the kneading disc region in front of the crest.
d) Particles enter the crest gap (at position 3 in each case).
e) Particles travel through the closing nip.

The axial flow against the conveying direction in principle correlates with the distributive mixing effect (kinematic distribution processes [1, p. 177]). However, the recognizable pressure-induced axial velocity increase at these trajectories (a, b and c) also has a slight dispersive effect, since there is a stretching flow.

According to Bernoulli's equation, negative pressure gradients result in a velocity increase. In the present example, the negative pressure gradient is the result of the counter-conveying effect of the connecting left element and the addition of the local pressure extremes of the adjacent kneading discs. Because of the convergent geometry between the kneading disc flank and the barrel wall, a local pressure maximum occurs in front of a pushing flank.

Behind a drawing flank, on the other hand, is a pressure minimum [1, p. 335]. This reduced pressure ensures that the trajectories b are entrained with the flank and therefore run shallower than the trajectories a. The movement against the direction of rotation (e.g. rotation of the trajectories a) can be explained by means of small localized turbulences directly in front of the face edge.

The velocity increase when passing through the nip (trajectories e) is shown by the stretching rates generated in this region of the kneading elements.

Figure 7 shows the corresponding consideration for a modified geometry. The new flank faces in the rotation direction. Since the crest is narrower, the identically colored lines are each significantly closer together. The underlying experimental conditions of the two representations **(Figs. 6 and 7)** are equivalent.

For a comparative analysis, it is clear that even slight changes in the kneading element lead to significant differences in

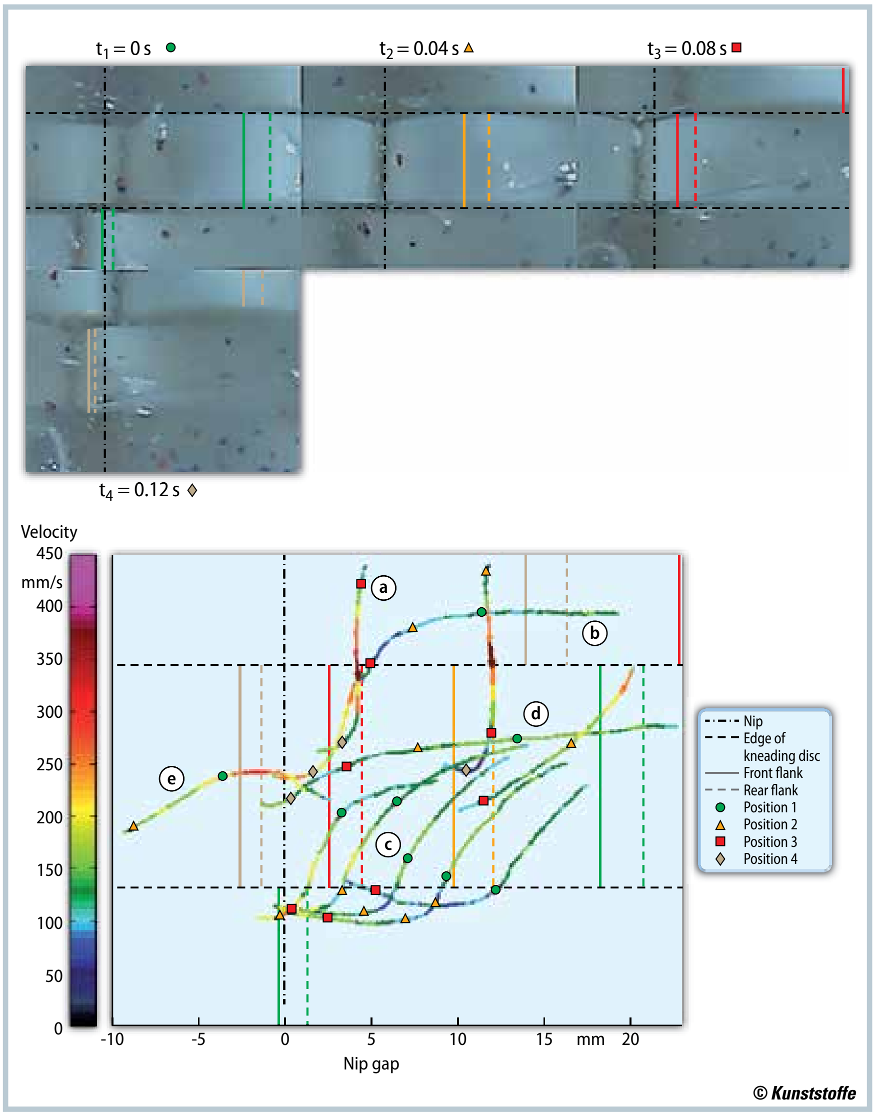

Fig. 7. Flow processes at an individual modified kneading disc (see above)

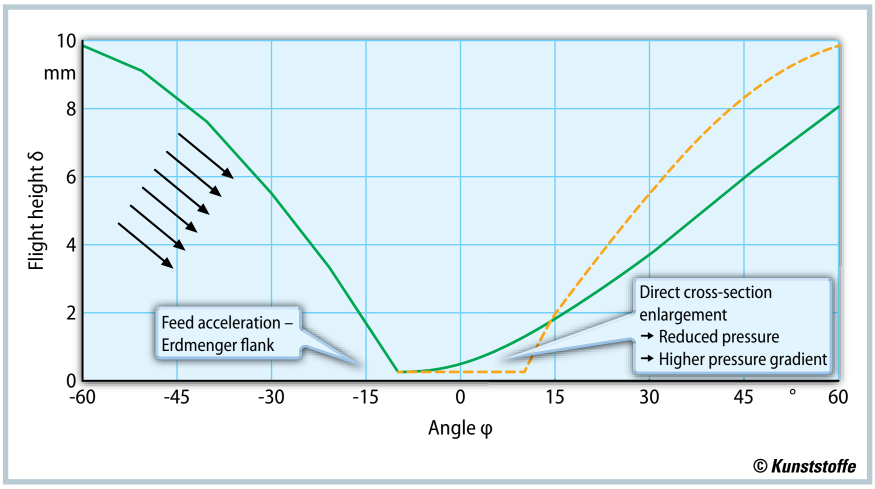

Fig. 8. Illustration of diffusor geometry

the flow pattern. The most serious differences can be seen for the trajectories c. Both the outlet angle and the outlet velocity depart significantly from one another.

To assess the processes on the flanks regarding stretching flow, it continues to be necessary to determine the relative velocity of the fluid in the direction of the screw gap (play between the barrel wall and the kneading disc crest) (trajectory d). This results in a minimally improved feeding acceleration in the crest gap, in case the modified flank faces against the direction of rotation of the screw shaft. That can be explained by a diffusor effect. The effect is achieved by means of a significantly narrower crest. There is therefore an increase in cross-section immediately following the narrowest point. **Figure 8** shows the flight height δ against the angle φ of the developed barrel inner wall. The diffusor geometry is recognizable. The subsequent cross-section enlargement ensures a higher pressure gradient, as a result of which a greater velocity increase along the flow path can be observed.

Summary and Outlook

In summary, it can be seen that the experimental set up, including the FDM prototypes, represent a fast and cost efficent method of quantitatively analyzing the flow and transportation processes on the elements of a co-rotating twin-screw extruder. The recognized tendency of the diffusor effect promises an optimization of the stretching rates in the feed acceleration into the crest gap. If the modified flank faces in the rotation direction, however, no improvement of stretching flow can be seen in the series of trials.

Following on from this test set-up, studies should now be carried out on metal element geometries with thermoplastic melts to give conclusive assessment of the geometry variants. ■