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Analysis of Spiral Mandrel Dies with Novel Channel Geometries to Draw Conclusions on the Purging Time of the Melt Using CFD

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Analysis of Spiral Mandrel Dies with Novel Channel Geometries to Draw Conclusions on the Purging Time of the Melt Using CFD

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Abstract: Spiral mandrel dies are deeply integrated into the extrusion process and are the predominant die type for manufacturing products with a ring-shaped cross-section, e.g. blown film. The geometry of the axial spiral mandrel die is characterized by a spiral mandrel with one or more feed holes that merge into the spiral channels. The spiral channels themselves are embedded in the mandrel and have a characteristic u-shape in cross-section, which is dictated by the milling head used during manufacturing. In the past, numerous geometric parameters of the conventional axial spiral mandrel distributor have been examined in the course of optimizations, but the general design is still largely based on the concept of the 1960s. Therefore, this paper presents four concepts for new channel geometries that deviate from the conventional spiral channel cross-sectional shape. All variants were analyzed using a CFD-based algorithm for the automated geometry optimization by varying the general parameters describing the spiral channel. Other defining parameters were kept constant. The results provide insights into the influence of geometry parameters for spiral mandrel dies on purging time.

Keywords: Extrusion, Die Design, Spiral Mandrel Die, Novel Channel Geometries, Purging, CFD, Simulation, Optimization, Parameter Study, Plastics Processing, Plastics Machinery

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Introduction

In the extrusion process, purging of the extrusion die is often carried out on-line during operation, as this practice is faster than a die change. However, this can lead to long purging times if the extrusion tool has not been specifically optimized in terms of its purgeability. Long purging times are associated with lost production and wasted material and not only affect productivity, but also increase production costs and impact the environment. Optimizing the purgeability of extrusion dies such as the spiral mandrel die is therefore of significant importance to minimize these negative effects and increase the efficiency and sustainability of production.

Approach

The intention of this paper is to investigate novel channel geometries for axial spiral mandrel dies. The overall research objective is to optimize the purgeability of the spiral mandrel distributor, which is why purgeability is used as a quality criterion to evaluate the results for the different geometry variants. The integration of this quality criterion will be discussed later in this paper.

The following investigation is based on the fully parameterized CAD models of the tool variants considered. From these, a total number of 3886 unique design points (DP) with novel channel geometries are generated, which are then transferred individually to the ANSYS Workbench programs to perform the CFD simulations in ANSYS Fluent. The results of the simulations are processed and saved in the form of quality criteria. This process of the described parameter study is illustrated in Figure 1.

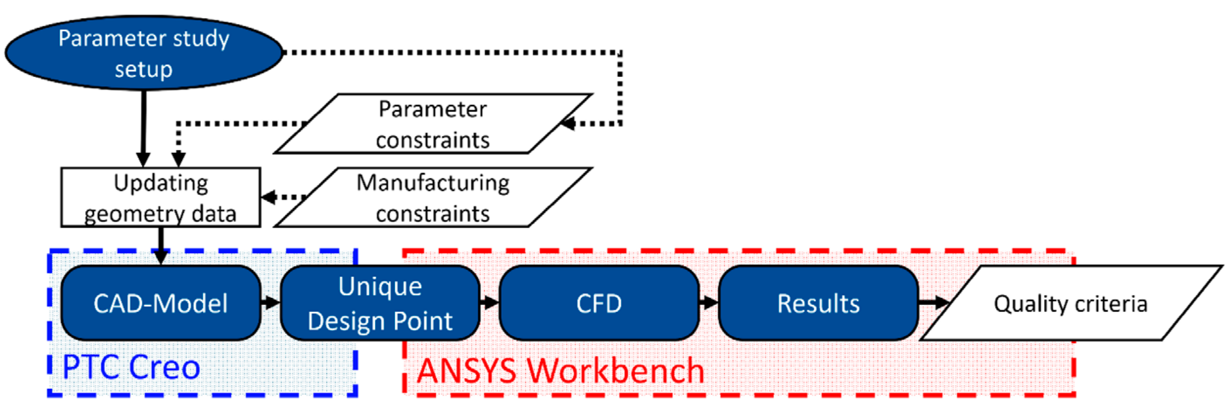

Figure 1. Algorithm for the conducted parameter study.

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Analyzed Geometries

This paper examines four variants of an axial spiral mandrel die. The CAD model of the conventional axial spiral mandrel distributor was created in PTC Creo and is the subject of work by te Heesen et al. [1,2]. The variants investigated in this paper differ from the conventional design in the cross-sectional shape of the spiral mandrel channel. Four CAD models were used, each representing one of the cross-sectional shapes. Within these models, the parameters describing the basic geometry as well as those defining the channel geometry can be freely changed. Only the fluid volume was modeled, as this forms the flow domain for the subsequent CFD simulation. Since the spiral mandrel manifold has a periodicity, only a 90° segment was modeled for the considered die with four feed holes to reduce the simulation time. The investigated channel geometries and the describing geometry parameters are shown in Figure 2.

The naming of the different variants also refers to these cross-sectional shapes, which differ from the conventional crest shape shown as variant (a) in Figure 1. The relevant geometry parameters for the geometry variants (a) to (e) are listed in Table 1. A distinction is made between the parameters that were varied during the investigation to generate different DP and those that were kept constant to ensure comparability of the results. In addition, the minimum and maximum values, as well as the step sizes with which the respective parameters were varied.

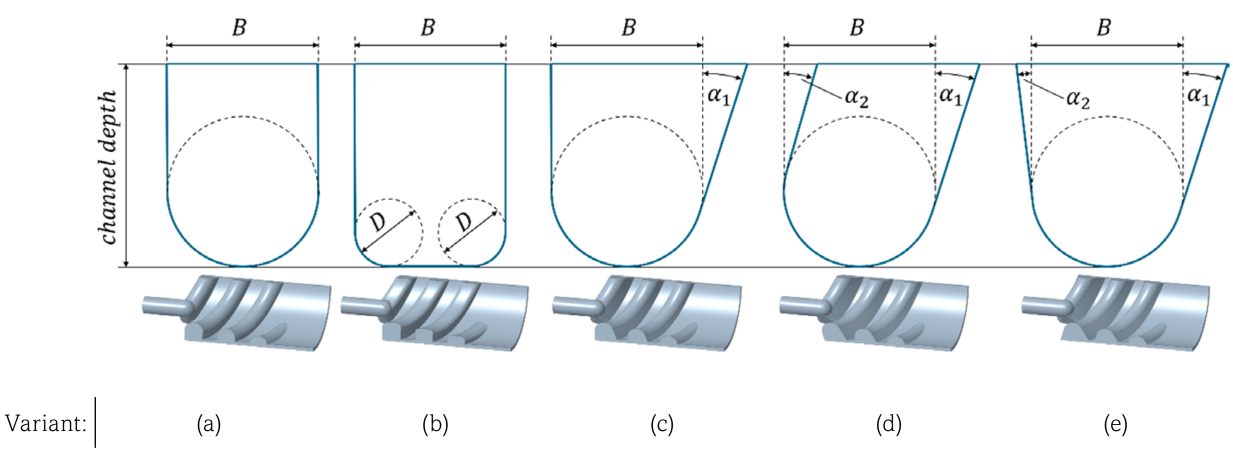


Figure 2. Cross-sectional shapes within the spiral channel: (a) conventional crest-shape, (b) double-circle crest, (c) one-sided flank angle, (d) two-sided flank angle “Parallelogram,” (e) two-sided flank angle “Pyramid.”

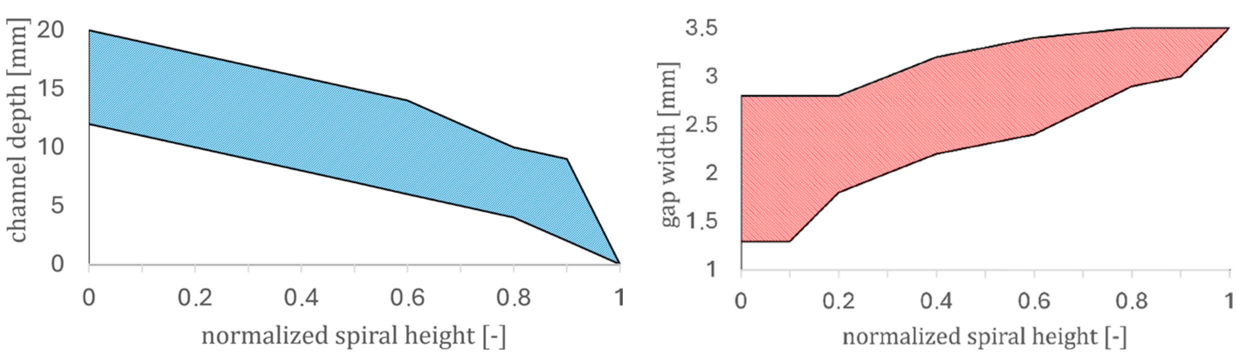
Table 1. Excerpt of the parameters used in the study to describe the channel geometry.

Parameter	Type	min	max	Step size
D [mm]	Variable	4	16	2
α_1 [°]	Variable	5	40	5
α_2 [°]	Variable	5	40	5
B [mm]	Fixed	18	18	-
channel depth$_n$ [mm]; n = [0 ..1]	Function		See Figure 3	
gap width$_n$ [mm]; n = [0 ..1]	Function			

The channel depth and the gap width change depend on the spiral height and are described by a continuous function for each DP. The index n describes the normalized spiral height n assumes values between 0 and 1. These values act as supporting points and are used to describe the spiral channel depth and the gap width at the different heights. Different values for channel depth and gap width can be assumed at each supporting point. The considered value range is highlighted in Figure 3.

Other characteristic parameters for the spiral mandrel die, like the total die height, feed length, spiral height, outer diameter, and wrap angle, as well as the number of channels and the gap width at the outlet were kept constant.

For a general description of the axial spiral mandrel die and the parameters describing the geometry, refer to the works of te Heesen et al. [1,2] and Michaeli et al. [3].



(a) (b)

Figure 3. Channel depth (a) and gap width (b) as a function of the normalized spiral height.

Simulation Set-up and Boundaries

The CFD simulations were performed in a steady state for a total mass flow of 40 kg/h. The material parameters for the low-density polyethylene used (Lupolen 2420D – LyondellBasell Industries) were imported into the solver via a user-defined function and included data on density, heat capacity, thermal conductivity and viscosity, using a cross-WLF model. Figure 4 shows the applied boundary conditions for the reference geometry.

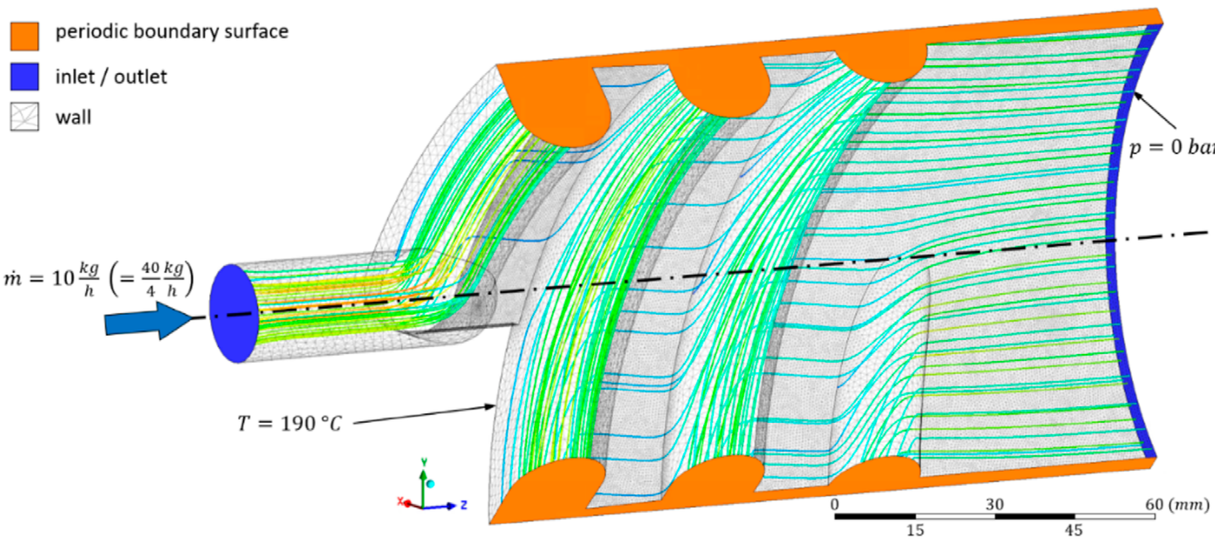


Figure 4. Boundary conditions for the spiral mandrel die.

Quality Criteria Used for the Evaluation

As the focus of the study is on purgeability, the fluid change effectiveness (FCE) is used as an evaluation criterion to identify and quantify stagnation zones. The FCE ε is based on the work of Kummerow et al. [4] and describes the ratio of the mean absolute residence time τ to the local melt age θ for each cell in the flow domain. Therefore, the FCE describes how often a local volume is purged in the time it takes for a plug flow to flow through the entire volume:

$$\varepsilon = \frac{\tau}{\theta} = \frac{\overline{\theta}_{outlet}}{\theta} \qquad 1)$$

The combined volume of all cells with a purgeability below a threshold value ε is referred to as V_ε and is normalized by the total volume of the fluid domain V_{total}. The resulting value Q_ε can then be used as a quality criterion for different values of ε:

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$$Q_\varepsilon = \frac{V_\varepsilon}{V_{total}} \quad (2)$$

For example, $Q_{\varepsilon = 0.2}$ describes the percentage of fluid volume that is replaced less than 0.2 times by a plug flow. In other words, this percentage of the fluid volume cannot be replaced with five plug flows, passing through the die. The aim is therefore to minimize the value of Q_ε. In this work, 16 quality criteria were calculated for each DP to describe the purgeability in the range between $Q_{\varepsilon = 0.025}$ and $Q_{\varepsilon = 0.4}$.

Results of the Simulations

The linear correlation coefficient is used to evaluate the results of the geometry variants and in particular the relationship between purgeability and the geometry parameters. This is calculated between all geometry parameters and the 16 quality criteria of Q_ε. For each geometry parameter, the correlation is then summarized to an averaged correlation coefficient $\bar{r}$. These aggregated correlation coefficients are listed in Table 2.

Table 2. Linear correlation coefficients for parameters describing the channel geometry.

Parameter \ Variant	(b)	(c)	(d)	(e)
D [*mm*]	-0.64			
α_1 [°]		-0.36	-0.21	+0.11
α_2 [°]			-0.14	+0.46
channel depth$_n$ [*mm*]; n = [0 .. 0.3]	+0.14	+0.33	+0.40	+0.34
gap width$_n$ [*mm*]; n = [0 .. 0.3]	+0.16	+0.20	+0.24	+0.15

To evaluate the results, variants (b) and (e) are discussed first. For (b), the negative correlation between the rounding radius D and Q_ε shows that an increase in D results in improved purgeability. It should be noted that for large values of D, the geometry of the double-circle crest approaches that of a conventional crest shape. In terms of purgeability, the double-circle variant offers no advantages over the conventional cross-section (a) and can be discarded for further optimization.

The same applies to the geometry of (e): here, the back flank angle α_2 proves to be the most disadvantageous parameter for purgeability; the best results are achieved with the smallest flank angles. The preferred geometry variant of (e) is therefore variant (c), which effectively has a back flank angle α_2 of 0°.

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As for variant (c), a negative mean linear correlation coefficient exists between the values of Q_ε and the flank angle α_1 ($\bar{r} = -0.36$). Thus, higher values of α_1 can lead to better purgeability. However, the flank angle α_1 cannot be increased indefinitely to improve purgeability. Hence, a non-zero optimum exists, which is dependent on the other geometry-determining parameters. Accordingly, variant (c) is suitable for further consideration in future investigations.

Finally, geometry variant (d) will be evaluated here. Negative correlations with purgeability were found for both α_1 ($\bar{r} = -0.21$) and α_2 ($\bar{r} = -0.14$). However, these are significantly lower than the influence of the initial gap width and the initial spiral depth. Increasing both the outlet-side flank angle and the inlet-side flank angle can contribute to improved purgeability. Further research is also advisable here.

For future research, variant (c) can be investigated as a subset of variant (d) by extending the value range by the value $\alpha_2 = 0°$. The recommendations from the exclusion of variants (b), (e), and (c) for future investigations in favor of variants (a) and (d) are shown in Figure 5.

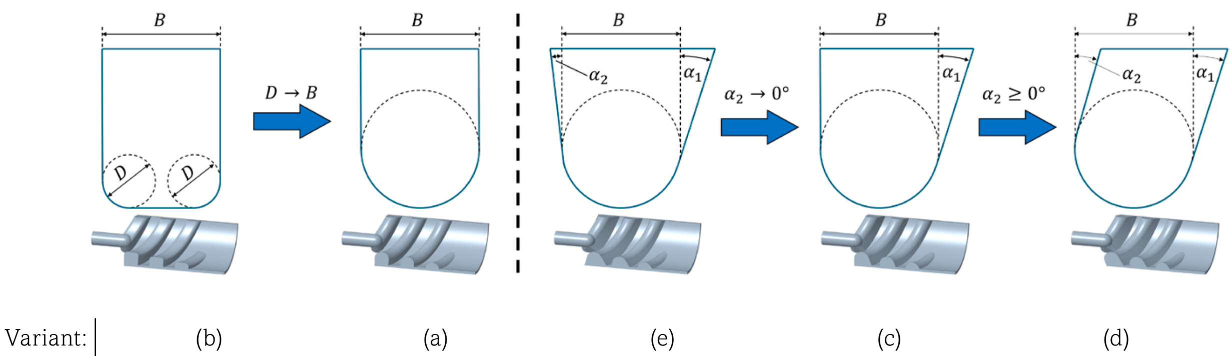

Figure 5. Recommended exclusion of variants (b), (e), and (c) in favor of variants (a) and (d).

Conclusion and Outlook

Based on the results presented, this paper shows that the channel shape in the spiral channel has a fundamental influence on purgeability and should be considered in the context of detailed die optimizations. It has already been shown that a reasonable design decision to improve purgeability is the integration of flank angles. Spiral channels that are inclined in the direction of the die outlet have proven to be advantageous.

The geometry variant (b) of the double-circle crest could not lead to any improvement in purgeability and can be excluded for future optimizations. The variant (d) of the two-sided flank angle "Parallelogram" offers the greatest potential for optimizing the spiral channel. In future studies, detailed investigations of the interactions between the angles of the outlet-side and inlet-side flanks must

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be carried out, and the optimum must be determined as a function of the gap width and channel depth profile, as well as the other geometry parameters. The interaction of purgeability with other quality parameters for the spiral mandrel die, such as pressure loss and mass flow homogeneity of the melt at the outlet, should also be investigated. Finally, the results of the simulations must be subjected to experimental validation.

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