SIMULATIVE EVALUATION OF THE TEMPERATURE INFLUENCE ON DIFFERENT TYPES OF PRE-DISTRIBUTORS IN SPIRAL MANDREL DIES

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Abstract

Thermal inhomogeneities in spiral mandrel dies, which occur especially in the pre-distributor, can lead to an uneven flow distribution despite a rheologically optimized design of the die. Against this background an integrative thermal and rheological flow simulation has been developed at the IKV, in which the whole pre-distributor can be modelled non-isothermally. The simulation takes both the non-linear flow behavior of the melt and the thermal phenomena in the die material into account.

In this contribution, the developed simulation model is used to evaluate and compare the temperature influence on the melt distribution in three different types of pre-distributors. These are a 2³-pre-distributor of a radial spiral mandrel die, a 2⁴-pre-distributor of an axial spiral mandrel die and a star pre-distributor with vertical redirection. The simulations show that in case of the 2³- and 2⁴-pre-distributor, both the external tempering of the die and the dissipative shear heating lead to an uneven temperature distribution in the melt and thus cause an inhomogeneous melt pre-distribution. In case of the star pre-distributor, the die tempering has no significant effect on the flow distribution. However, the dissipation leads to an uneven heat-up of the melt in the area of the redirection, which results in an uneven melt flow at the outlets of the pre-distributor.

In the next step, thermal design measures are introduced into the pre-distributors in order to homogenize the flow rate distribution at the outlets of the pre-distributors. By integrating heater cartridges, brass inserts and insulating gaps into the die, a more homogeneous flow rate distribution at the outlet of each pre-distributor can be achieved.

Introduction

In blown film extrusion, the extrusion die is almost exclusively a spiral mandrel die [1]. The main goal in the design of the spiral mandrel die is to ensure a uniform velocity distribution at the die outlet [2]. However, a simple rheological analysis of the die assuming isothermal conditions is not sufficient. Thermal inhomogeneities in the die due to the external heating of the die and the uneven shear heating in the flow channel can lead to an uneven flow in spite of a rheological die design [3]. The thermal inhomogeneities occur especially in the pre-distributor of the die, whose task is to divide the melt stream delivered by the extruder into multiple sub-streams, which are then fed into to the mandrels of the following main distributor [4].

The temperature influence on the flow balance in extrusion dies has been addressed in a number of scientific studies. Charlton et al. pointed out that the die land temperature in the profile extrusion of highly filled recycled polypropylene has a significant influence on the flow balance and process stability [5]. Skabrahova et al. simulated the non-isothermal flow in an axial spiral mandrel die and showed that a non-uniform temperature distribution can negatively influence the flow balance [6]. The analysis of the flow in a spiral mandrel die by Sun and Gupta lead to the finding that the viscous heating leads to a non-uniform temperature distribution in the flow channel, which can affect the flow balance [7]. Catherine simulated the non-isothermal flow in a flat film die with inhomogeneous melt temperature at the die inlet [8]. The simulations show that the inhomogeneous temperature leads to a significantly uneven flow rate distribution at the die outlet. In conclusion, the temperature influence on the pre-distribution in spiral mandrel dies is not negligible and should be taken into account in the die design.

In order to analyze the temperature influence on the pre-distribution in spiral mandrel dies, an integrative simulation model was developed and successfully validated at the Institute of Plastics Processing (IKV), which depicts the whole pre-distributor non-isothermally [9]. The simulation takes both the heat transfer in the die and the shear heating in the melt into account. In this contribution, the developed model is used in order to analyze and compare the temperature influence in different types of pre-distributors.

Governing Equations

For a mathematical description of the non-isothermal flow in the pre-distributor, the conservation equations for mass, momentum and energy are used [10]. For the simultaneous solution of the conservation equations, it is necessary to link them via constitutive equations. For the connection of the mass and momentum conservation, the Carreau law is used as a rheological material law [11]:
\[
\eta = \frac{A}{(1 + B \cdot \dot{\gamma})^C}
\]  

where \( \eta \) is the shear viscosity (Pa\(\cdot\)s), \( \dot{\gamma} \) is the shear rate (1/s), and \( A, B \) and \( C \) are material constants derived from the viscosity curves of the material. The influence of the temperature on the shear viscosity is modelled with the temperature shift according to Williams, Landel and Ferry (WLF equation) [12]. If heat transfer processes occur in a flow, an additional thermodynamic equation of state is required, which describes the relation between the thermodynamic state variables pressure, density and temperature. Plastics melts are hereby usually modelled as incompressible fluids, whose density is independent of the pressure.

The relevant heat transfer processes for the integrative simulation of the spiral mandrel die are the heat conduction in the die and melt as well as the heat exchange of the outer surfaces of the die with the environment by means of convection and radiation. The heat conduction is described by the Fourier’s law, whereas the convective heat exchange is modelled by Newton’s law of cooling [13]. The radiative heat exchange with the environment can be described with the Stefan-Boltzmann law [14].

**Simulation Models and Material**

The above-mentioned equations are solved with Finite-Elements software Polyflow (ANSYS) for three different types of pre-distributors. The first one is the \(2^3\)-pre-distributor of a radial spiral mandrel which is shown in Figure 1. In this pre-distributor, three distribution levels are used to feed a total of eight spiral channels in the main distributor. The circumferential surface of the die is covered by a heating tape in the actual extrusion process.

The second pre-distributor is the \(2^4\)-pre-distributor of an axial spiral mandrel die, which has four distribution levels and can feed 16 spiral channels (Figure 2). Furthermore, a star-pre-distributor with 8 sub-channels and a vertical redirection of the flow channel as shown in Figure 3 is analyzed. In the integrative simulation of the pre-distributors, both the flow channel and the surrounding die material are depicted. Here, the symmetry of the system is used and, therefore, only one half of each pre-distributor is depicted. In an actual die, the main-distributor would be downstream the pre-distributor. It is desirable to simulate the whole die consisting of pre- and main-distributor. However, in Polyflow no numerical convergence can be achieved in case of a non-isothermal simulation of the whole die. That is why the following simulations only depict the pre-distributors. Hereby, nozzles are positioned at the outlets of the pre-distributors in order to simulate the pressure loss of the main distributor.

In the simulations, both thermal and rheological boundary conditions for the flow channel and thermal boundary conditions for the die material must be specified. Regarding the rheological boundary conditions in the flow channel a steady-state, laminar, wall adhesive flow is assumed. The flow at the inlet of the pre-distributor is assumed to be fully formed and the total mass throughput through the die is given. At the nozzle outlets there is ambient pressure. In addition to these rheological boundary conditions, it is also necessary to define thermal boundary conditions for the flow channel.
At the inlet of the flow channel a constant melt temperature is assumed. Within the melt, heat conduction and dissipative shear heating occur. The flow channel wall is defined as the interface between the flow channel and the die material, where a convective heat exchange between the plastics melt and the die steel occurs. This heat exchange is calculated explicitly in the simulation as the simulation model includes both the flow channel and the surrounding die material.

In case of the thermal boundary conditions of the die, the circumferential surface of the dies, which are covered by a heating tape in the actual process, are imposed with a homogeneous temperature. The remaining outer surfaces of the dies exchange heat with the environment by free convection and radiation. This heat exchange is modelled in the simulation with Newton’s law of cooling, whereby a combined heat transfer coefficient for convection and radiation is used. The convective heat transfer coefficient was estimated with the help of an empirical equation for the Nusselt-number [8], whereas the heat transfer coefficient for the radiation was derived from the Stefan-Boltzmann law. There is also a heat exchange in the cooling air duct of the dies by forced convection, which is described by Newton’s law of cooling.

The plastics used in the simulation is a high-density polyethylene (HDPE) with a melt flow rate (MFR) of 3.1 dg/min (190 °C, 5 kg) manufactured by LyondellBasell GmbH. Its temperature and shear rate-dependent viscosity is described by the Carreau law and the temperature shift according to the WLF equation. In Figure 4 the measured viscosity curves are shown. A clear influence of the temperature on the viscosity can be observed. The corresponding model parameters at the reference temperature \( T_0 \) and the thermal properties of HDPE are shown in Table 1. The thermal properties are modelled as temperature-independent and are either measured (density \( \rho \)) or taken from literature (specific heat capacity \( c_p \) and heat transfer coefficient \( k \)). In the simulations, the process parameters mass throughput \( \dot{m} \), melt temperature at the die inlet \( T_M \), and the temperature of the circumferential surface of the die \( T_W \) are varied.

### Table 1. Shear viscosity model parameters and thermal properties of HDPE.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A ), Pa(s )</td>
<td>9472.83</td>
</tr>
<tr>
<td>( B ), s</td>
<td>0.1871</td>
</tr>
<tr>
<td>( C )</td>
<td>0.655</td>
</tr>
<tr>
<td>( T_0 ), °C</td>
<td>200</td>
</tr>
<tr>
<td>( T_S ), °C</td>
<td>-35.9</td>
</tr>
<tr>
<td>( \rho ), g/cm(^3)</td>
<td>735.8</td>
</tr>
<tr>
<td>( c_p ), kJ/(kg(K))</td>
<td>3</td>
</tr>
<tr>
<td>( k ), W/(m(K))</td>
<td>0.256</td>
</tr>
</tbody>
</table>

### Simulation Results

#### Analysis of the Temperature Influence

First, the temperature influence on the radial 2\(^3\)-pre-distributor is analyzed. On the left side of Figure 5 the calculated temperature distribution in the pre-distributor is shown exemplary for the process point (\( \dot{m} =300 \) kg/h, \( T_M= T_W=200 \) °C). The shear heating induces an increase of the melt temperature near the flow channel wall in the first part of the flow channel. Here, the flow channel side, which is directed towards the outer edge of the die, is heated more due to the greater flow channel length, which results in a stronger dissipative heat-up. Afterwards, the subsequent branching of the flow channel causes that the increased temperature remains only on one channel side in each branch. On the other flow channel side colder melt from the middle of the flow channel before the branching flows. The warmed melt part flows in the direction of outlets 2 and 3, while the relatively colder melt part flows toward the other two outlets. The result is that outlet 3 has the highest melt temperature and outlet 1 and 4 the lowest.

![Figure 5. Temperature and throughput distribution in the 2\(^3\)-pre-distributor (\( \dot{m} =300 \) kg/h, \( T_M= T_W=200 \) °C).](image)

As shown on the right side of Figure 5, the temperature distribution is also reflected in the flow rate distribution at the outlets. Outlet 3 has the highest temperatures and therefore the lowest flow resistance, because of which the highest output is also at outlet 3. At outlet 1 and 4 on the other hand, which have the lowest...
melt temperatures, are the lowest flow rates. The overall result is a difference between the maximum and minimum throughput of approximately 3.7 % of the average throughput.

Figure 6 shows, that the external heating of the die has a similar effect as the dissipation. In case of an outer die temperature \( T_W \) that is higher than the melt inlet temperature \( T_M \), a significant temperature gradient results in the die with flow channel wall temperatures above \( T_M \). This leads in analogy to the dissipation to an increase of the melt temperature near the flow channel wall in the first part of the flow channel. The subsequent branching again leads to the situation, in which hotter melt flows to the outlets 2 and 3, whereas at outlets 1 and 4 the melt temperature is lower.

![Figure 6. Temperature and throughput distribution in the 2\(^3\)-pre-distributor (\( \dot{m} =300 \text{ kg/h}, T_M=200 \degree\text{C}, T_W=220 \degree\text{C}) \)](image)

As the right side of Figure 6 shows the combined influence of dissipation and external heating leads to an uneven throughput distribution at the outlets of the pre-distributor with a difference between the maximum and minimum throughput of approximately 8.5 %. Hereby, the maximum throughput can again be observed at outlet 3 whereas the lowest throughputs are at outlet 1 and 4. Accordingly, the external heating has qualitatively the same effect on the throughput distribution as the dissipation and therefore complements the dissipation induced inhomogeneities.

In case of the 2\(^4\)-pre-distributor of the axial spiral mandrel die, similar results can be seen. Figure 7 shows the temperature distribution in the pre-distributor for the process point (\( \dot{m} =300 \text{ kg/h}, T_M=200 \degree\text{C}, T_W=220 \degree\text{C})\). The melt is first heated up in the first channel section near the flow channel walls due to the dissipation and higher die temperature. The subsequent branching causes the temperature maximum in each sub-channel to remain on only one side. On the other side of each sub-channel, there is colder melt, which was in the middle of the flow channel before the branching. However, the region of this partial flow, which directly adjoins the flow channel wall after the branching, is heated up along the remaining flow path. This results in three groups with respect to the temperature level at the outlets of the pre-distributor: the highest melt temperatures can be found at the outlets 1 and 8 since the melt flowing through these outlets was heated continuously throughout all distributor planes. The next highest melt temperatures are observed at the outlets 4 and 5. This melt part experiences a significant heating only after the first branching. The lowest melt temperatures occur at the outlets 2, 3, 6 and 7, since they are flowed through by melt which, with the exception of the last distribution plane, always flowed in the flow channel center and was therefore hardly heated in the course of the pre-distributor.

![Figure 7. Temperature distribution in the axial 2\(^4\)-pre-distributor (\( \dot{m} =300 \text{ kg/h}, T_M=200 \degree\text{C}, T_W=220 \degree\text{C}) \)](image)

It should be noted that in case of the axial 2\(^4\)-pre-distributor, there is a pronounced temperature gradient in circumferential direction: The die temperatures in the areas near the inlet (left side in Figure 7) are significantly lower than in the more distant areas (right side of Figure 7). This also influences the melt and causes the outlets 5 to 8 to have higher melt temperatures than the outlets 1 to 4. This is reflected in the throughput distribution shown in Figure 8.

![Figure 8. Throughput distribution in the axial 2\(^4\)-pre-distributor for different total throughputs (\( T_M=200 \degree\text{C}, T_W=220 \degree\text{C}) \)](image)

It can be seen that the highest throughputs are at outlet 1 and 8 and the lowest throughputs are present at outlet 2, 3, 6 and 7. Here, the throughputs of the outlets 5 to 8 are higher than the corresponding throughputs of the inlet-close outlets. Responsible for the latter is the aforementioned temperature gradient in the
circumferential direction. The maximum throughput difference has a value of 5.5 % at a total throughput of 300 kg/h. It should be noted, that the throughput deviations increase with increasing total throughput. This is due to the stronger dissipation at higher flow rates. This effect can also be observed in case of the radial 2\(^1\)-pre-distributor.

In contrast to the 2\(^n\)-pre-distributors, the throughput distribution of the star-pre-distributor is not influenced by the value of the outer die temperature \(T_W\). However, a significant effect of the dissipation can be observed as shown in Figure 9. The dissipation increases the melt temperature near the flow channel walls. In the area of the vertical redirection of the flow channel, the melt is heated up more along the outer radius of the redirection than along the inner radius due to the longer flow path at the outer side. Because of this, the melt part that flows to outlet 5 has a higher temperature than the melt at the remaining outlets. That is why the throughput at outlet 5 is also greater than at all the other outlets. The difference between the maximum and minimum throughput deviation has a value of 4.3 %.

The thermal design measures can also be transferred to the other types of pre-distributors and improve their throughput distribution. In Figure 11 the temperature distribution in the axial 2\(^3\)-pre-distributor with heater cartridges is shown. The installed heater cartridges lead to a significant homogenization of the temperature distribution in the melt. In this way, the maximum throughput difference is reduced from 5.5 % to 0.2 %. However, the high number of heater cartridges is unfavorable in this solution. One possibility for reducing the required number of heater cartridges is to integrate insulating recesses into the axial pre-distributor in analogy to the radial pre-distributor. In this way the effect of the external heating and thereby the required amount of heater cartridges could be reduced.

In case of the star-pre-distributor, since the inhomogeneities are primarily caused by the dissipative shear heating and the influence of the die tempering is negligible, the use of insulating recesses is not suitable.
Therefore, only heater cartridges are used as thermal design measures. By installing heater cartridges near the inlet, the temperature distribution in the pre-distributor can be homogenized as shown in Figure 12. In this way, the maximum throughput difference can be reduced from 4.3 % to 0.4 %.

![Figure 12. Temperature and throughput distribution in the star-pre-distributor after optimization (m =300 kg/h, T_M=T_W=200 °C).](image)

**Conclusions and outlook**

The integrative simulation of the pre-distribution in spiral mandrel dies shows that the thermal inhomogeneities in the pre-distributor lead to an uneven throughput distribution in the following main-distributor. In case of 2ⁿ-pre-distributors of axial or radial spiral mandrel dies, both the dissipative shear heating and the external die tempering lead to an uneven throughput distribution at the outlets of the pre-distributor. In case of the star-pre-distributor, the external heating has no effect on the throughput distribution. However, there is a significant influence of the dissipation.

The aforementioned inhomogeneities can be compensated by installing heater cartridges, brass inserts and insulating recesses into the die. In this way, the temperature distribution in the sub-channels is equalized, which in turn homogenizes the throughput distribution in the pre- and main distributor significantly. Thus, the efficiency of the blown film extrusion can be increased and the quality of the films produced can be improved.

In future works, the numerical modelling of the whole die, consisting of pre- and main-distributor, should be considered. As Polyflow is not suitable for this, the usage of alternative software such as polyXtrue (Plastic Flow, LLC) should be evaluated.

Another topic for future works is the investigation of alternatives to the thermal design measures for the flow homogenization. One possibility is to transfer the concept of melt flippers from injection molding to spiral mandrel dies. Melt flippers are used in injection molding in order to homogenize temperature variations that form in the runner of the mold in analogy to 2ⁿ-pre-distributors. The melt flippers are integrated into the mold between the individual runner branchings and lead to a rotation of the melt stream between the branchings. In this way, the different melt regions can be strategically rearranged which nullifies the temperature variation across the melt. This concept could also be used to reduce the thermal inhomogeneities in the pre-distributor of spiral mandrel dies. Another alternative design measure for the flow homogenization would be to integrate adjustable flow resistances at the end of the individual flow channels of the pre-distributor such as adjustable pins that protrude into the flow channel. By individually adjusting the protruding length of each pin, the thermally induced throughput differences in the pre-distributor could be compensated.

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**References**