OPTIMIZATION OF A PROFILE COEXTRUSION DIE USING A THREE-DIMENSIONAL FLOW SIMULATION SOFTWARE

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Abstract

Die geometry of a bilayer die for coextrusion of a PVC window profile is optimized for a uniform exit velocity distribution by using a flow simulation software. Besides the flow inside the die, the post-die flow of extrudate, including the flow in the calibrator of the profile die, is simulated. The pressure drop and the changes in the extrudate shape predicted by the software are in good agreement with the corresponding experimental data. It is estimated that the initial optimization of the die using the software saved two fine-tuning cycles in the experiments, resulting in a significant saving in the cost and the lead time for the profile die development.

Introduction

The main goal in the design of a die for extrusion of a complex profile is to get a uniform velocity distribution at the die exit (die balancing) [1]. If the velocity at die exit is different in different portions of the profile, the polymer gets redistributed after it comes out of the die until a uniform velocity is obtained away from the die. In general, after the polymer leaves the die the thickness of the profile will increase at the locations with greater velocity and will decrease at low velocity locations. Besides this change in thickness, redistribution of the polymer after it leaves the die can also lead to a significant distortion in the profile shape beyond the die exit. If multiple polymers are coextruded through the die, the additional complexity in design of the coextrusion die is to develop the flow channel geometry in the die and in the feed block for each layer which will give the required layer structure in the final product. Therefore, a software package which can accurately predict the velocity distribution in the die along with the post-die distortion of the extrudate and the layer structure in the final product is an extremely valuable design tool for a die designer.

In the present work, extrusion die design software polyXtrue from Plastic Flow, LLC was used to optimize the design of a bilayer coextrusion die for a polyvinylchloride (PVC) window profile. Four flow simulations were performed to iteratively improve the die. The die geometry thus obtained was machined and the final fine-tuning of the die was performed experimentally. As discussed later in the paper, the four iterations of virtual fine-tuning is estimated to have saved two fine-tuning cycles of this die in experiments, resulting in a significant savings in cost and lead time for the die design.

Die Geometry

A coextrusion die used for production of a bilayer PVC window profile is analyzed in this work. The geometry of the coextrusion die analyzed is shown in Fig. 1. In Fig. 1, the core polymer enters the die from the circular entrance on the right, whereas the polymer for the skin layer enters from the rectangular entrance on top. The polymer entering from the top is split into two channels before meeting the core polymer to form thin skin layers on both sides of the profile.

The skin layer, which is the visible portion of this profile when installed on a window, is made from a virgin PVC compound. The polymer used for the core is a recycled PVC compound. The recycled material for the polymer used in the core is obtained from old PVC window profiles collected during renovation of old buildings. By reusing the PVC from old windows to make the profiles for new PVC windows, as shown in Fig. 2, Deceuninck has closed the PVC material loop.

The geometry of the bilayer profile die shown in Fig. 1 is quite complex. The main goal in design of the feed channel for the core polymer was to obtain a balanced uniform velocity distribution at the die exit. To provide the same amount of material on each side of the profile, as shown in Fig. 1, the feed channel for the core polymer was split vertically into two channels. The feed channel for the skin layer was designed such that the thickness of the skin layer is stable and a required minimum thickness of the skin layer is obtained over the complete length. In order to obtain a uniform thickness of the skin layer, the feed block for the skin layer is designed to accelerate the flow for the region of the skin layer that is away from the polymer entrance and to slow down the flow in the portion of the skin layer closer to the entrance. Thereby, the pressure drop is approximately equalized over the complete skin layer.

While designing the feed channels for the core and the skin layer, special attention is needed to prevent any flow stagnation (dead-zone) in the channel. The polymer in such stagnant regions of the flow gets degraded and is eventually charred inside the channel.

Mesh Partitioning Technique for Coextrusion Simulation

The main difficulty in simulation of a multilayer flow during coextrusion is enforcement of the different material properties of the two polymers, when an element in the finite element mesh is occupied by more than one polymer. For the coextrusion simulation presented in this paper, the mesh partitioning technique has been employed in the polyXtrue software for coextrusion simulation. In the mesh partitioning technique, the interface between adjacent polymer layers is represented by a mesh of triangular finite elements. This mesh of triangular elements is then used to partition the tetrahedral elements in the die which are intersected by an interface into two different finite elements. The two new elements generated by partitioning of an original tetrahedral element in the die can be tetrahedral, pyramidal or prismatic in shape. Further details of the mesh partitioning technique are available in earlier papers [2 – 6].

Once the finite elements, which are intersected by an interface, are partitioned into two different elements, the material properties on either side of the interface can be easily enforced in the simulation. Since the mesh of tetrahedral finite elements remains unaltered during the entire simulation, the mesh partitioning technique can easily simulate a multi-layer flow irrespective of the complexity of the die geometry or that of the layer structure in a coextrusion die.

Resin

As mentioned earlier, in the coextrusion die analyzed in this paper, a PVC resin was used for the core as well as the skin layer of the profile. The core is made-up of a recycled PVC, whereas a virgin PVC is used for the skin layer. However, the rheology and other material properties needed for the flow simulation are essentially the same for the virgin and the recycled PVC.

The viscosities (η) of the PVC employed, which is shown in Fig. 3, was modeled by the Cross-WLF equation given below [7].

$$\eta = \frac{\eta_0}{1+\left(\eta_0 \dot{\gamma}/\tau^*\right)^{1-n}} \quad (1)$$

$$\eta_0 = D_1 \exp\left[-\frac{A_1(T-T_a)}{A_2+(T-T_a)}\right] \quad (2)$$

where A_1, A_2, D_1, T_a, τ^* and n are material parameters, and $\dot{\gamma}$ is the shear rate. For the PVC used, the values of the material parameters are given in Table 1.

Results

The bilayer flow of PVC in the die geometry shown in Fig. 1 was simulated with the flow rate of 185.8 kg/hr in the core and 11.3 kg/hr in the skin layer. For the core as well as the skin layer, the temperature of PVC at the die entrances was specified to be 463 K, and the die wall temperature was 468 K. These flow rates and temperatures are the same as those used in the experiments. The flow in the extrudate beyond die exit, and also that in the calibrator was included in the simulation. The calibrator started at a distance of 1 cm from the die exit, and the length of the calibrator used in the simulation was 3 cm. In the 1 cm portion of the extrudate between the die exit and the calibrator, the stress-free condition was specified on all profile walls. To simulate the heat loss due to convection to the surrounding air in this portion of the extrudate, the heat transfer coefficient of 5 W/(m^2.K) and air temperature of 295 K was specified. In the calibrator, the external profile boundaries were enforced to slide along the calibrator without any friction, whereas the stress free condition was employed at all internal boundaries of the profile in the calibrator. Heat loss from the profile in the calibrator was again simulated by using the heat transfer coefficient of 5 W/(m^2.K) and calibrator wall temperature of 288 K. The finite element mesh used for the coextrusion simulation had 1,246,057 tetrahedral finite elements. On a Dell Precision M6700 laptop the simulation required 55 minutes of computation time when the CPU of the computer was used for the simulation. The simulation time was reduced to 29 minutes when the Graphical Processing Unit (GPU) of the computer was employed for the incompressible flow simulation portion of the finite element calculations. The computation time is expected to decrease further when GPU is also used for temperature and shear-rate calculations.

Fig. 4 shows the velocity distribution in ten different cross-sections of the flow domain used for the simulation, with one of the cross-section being at the die exit, one passing through the thin land region where the polymer for the skin layer contacts the core polymer for the first time, and the cross-section on the left being near the end of the calibrator. The velocity distribution at the die exit is also shown in Fig. 5. As mentioned before, the goal in the design of an extrusion die is to obtain a uniform velocity distribution at the die exit. But, with thickness of the profile wall being different in different portions of the profile, the exit velocity is expected to have some variation across the profile. As expected, the predicted velocity in the outer vertical walls of the profile, which have the largest thickness of 2.43 mm, is the highest and the velocity in the thin inner vertical walls (thickness 0.8 mm) is the smallest, with the velocity in the horizontal walls (thickness 1.98 mm) being in between. It should be noted that in the initial design of this die, the velocity along the outer vertical walls (shown in Fig. 6) was much larger than the velocity in this portion in the final die design in Fig, 5. The die geometry was improved iteratively based upon the predicted exit velocity distribution in each flow simulation iteration to obtain the exit velocity variation within an acceptable limit. It required four flow simulation iterations before the final die geometry shown in Fig. 1 was machined.

The evolution of the interface shape between the core polymer and the skin layer is shown in Fig. 7, which shows the interface shape starting from the lines of first contact between the two layers, to the die exit, in the extrudate beyond the die exit, and also in the calibrator. The predicted shape of the interface between the two layers at the end of the calibrator, which is the predicted final layer structure in the extruded part, is shown in Fig. 8. Fig. 8 also shows the predicted distortion in the profile shape (in red) at the end of the calibrator. A close-up of the profile shape and the layer structure in the left portion of the profile is shown in Fig. 9. The shape of the final profile, and the layer structure in the final product extruded in experiments from the die is shown in Fig. 10. To be able to see the layer structure in the final product, a colored PVC was used in the experiments for the core polymer of the profile shown in Fig. 10, even though the core and the skin layers are both white in the actual product. In the mesh partitioning technique, which was employed for the results presented so far, the polyXtrue software determines the shape of the interface based upon the streamlines starting from the nodes at the contact line where the two polymers meet for the first time. Since the streamline cannot be generated for the two die wall nodes at the two ends of the contact line, the interface shape in Figs. 8 and 9 ends slightly inside the profile. The interface shape can be extrapolated to the die walls for estimation of the interface shape in these portions of the profile. The layer structure predicted by the interface shape in Figs. 8 and 9 is in good agreement with the layer structure in the extrusion experiments in Fig. 10. In Fig. 8 and 9, since the external boundaries of the profile were forced to be in contact with the calibrator walls, the predicted shape of the external walls of the profile is the same as its shape at the die exit. The estimated deformation of the internal boundaries of the profile predicts an increase in the thickness of the outer vertical walls in the region where it meets the lower horizontal wall. This increase in the thickness of the outer vertical walls, which is expected because of the higher velocity at the die exit in this region in Fig. 5, was also observed in the profile extruded in the experiments (Fig. 10). Because of the lower exit velocity in the thin internal vertical walls, the thickness of these walls decreased in the experiments as well as in the simulation. In the experiments, in Fig. 10, these internal walls deformed outward in the extrudate. This outward movement of the internal walls is also observed in the predictions shown in Fig. 8 and 9. However, the predicted deformation of the inner walls is much smaller that the deformation observed in experiments. In the experiments, the internal surface opposite to the two vertical projections on the upper horizontal wall shows downward deformation. However, this downward deformation of the upper wall was not observed in the simulation because in the simulation the external profile surface, including the surface around the vertical projections, is enforced to be in contact with the calibrator wall. In the experiments, the vertical projections and the external profile surface near the projections have moved downward.

In the extrusion experiments with the feed block for the skin layer of this die, as shown in Fig. 11, stagnant flow and corresponding polymer degradation was observed in the two lower corners. Even though this stagnation in the flow was captured in the simulation results shown in Fig. 12, unfortunately this flow stagnation in the simulation results was not noticed before the die was machined. The flow stagnation was eliminated later from the skin layer feed channel by putting an insert and milling the feed channel again. As shown in Fig. 13, the stagnant flow in the feed channel for the skin layer was eliminated once the channel was re-machined.

Predicted pressure distribution in the die is shown in Fig. 14. As expected, at the die exit and in the extrudate beyond die exit, including the calibrator, the pressure is zero. The pressure increases towards the two entrances. In the experiments, the die had pressure transducers located near the entrances for the core polymer and the skin layer. The pressure values recorded at these two locations and the corresponding prediction for the pressure at the two die entrances, given below, are in excellent agreement.

	Experiments (MPa)	Simulation (MPa)
Core polymer pressure	35.4	36.1
Skin layer pressure	29.9	30.4

Temperature distributions in ten different cross-sections of the die are shown in Fig. 15. The temperature distribution at the die exit is also shown in Fig. 16. As mentioned earlier, temperature at the two entrances was specified to be 463 K, and the die wall temperature was 468 K. Starting with a temperature of 463 K at the two entrances, polymer temperature in feed channels for both layers slowly increase towards the die wall temperature of 468 K until the two layers meet in the die. Since the shear rate in the die after the two layers meet is quite high (see Fig. 17), a lot of heat is generated in this portion of the die due to viscous dissipation. Therefore, the temperature in the die increases beyond the die wall temperature after the two layers meet. Because of these viscous dissipations, a thin layer of high temperature polymer is formed near the die walls in this region. This thin layer of high temperature polymer near the die walls is clearly visible in the exit temperature distribution shown in Fig. 16.

Discussion

Before purchasing a license of the polyXtrue software about two years back, all profile dies at Deceuninck were fine-tuned experimentally to obtain the required profile shape and thickness distribution. In each of such tuning cycle, the flow channel in the die is modified by first plugging a portion of the channel by welding a piece of metal or by putting in an insert, and then re-machining the appropriate portion of the channel by wire EDM and by milling. Therefore, as expected, fine-tuning of a profile die experimentally is expensive and time consuming. At Deceuninck, each tuning of a profile die similar to the one discussed in this article costs about €3,000 ($3,750), and takes about 1 to 1.5 weeks of lead time. Virtual tuning of a profile die using a software is, of course, much simpler and takes much less time. As mentioned earlier, it took four virtual tunings for this profile die before the die shown in Fig. 2 was machined. Each virtual tuning requires changing the model for the flow channel in the die, setting up the simulation, and re-simulation of the flow. Depending upon the complexity of the die, each virtual tuning of a profile die may require from a few hours to about one day. The four virtual tuning iterations, including the generation of the model for the initial geometry, for the die discussed here were completed in less than a week. It is estimated that these four virtual tunings saved two tunings of this die in experiments, resulting in saving of about €6,000 ($7,500) and 2 to 3 week of the lead time for the die design. Before the polyXtrue software was purchased at Deceuninck, typically it required eight tunings to reach the final geometry for a coextrusion die. With the virtual fine-tuning using the software it now requires only five to six tunings.

Conclusions

A computationally efficient flow simulation software can be exploited as an effective design tool for optimization of complex profile extrusion dies. Even though the final fine-tuning of the profile still needs to be completed experimentally, initial virtual tuning of the die using a simulation software reduces the number of fine-tuning cycles in the experiments, resulting in significant savings in the cost as well as in the lead time for the die design.

References

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Table 1: Material properties of PVC

Viscosity parameters	
D_1 (Pa.s)	1.945×10^{14}
A_1	35.0
A_2 (K)	60.0
T_a (K)	348.0
τ^* (Pa)	2.94×10^{5}
n	0.188
Other material properties	
Density (kg/m^3)	1460.0
Heat Capacity (J/kg K)	1771.0
Thermal conductivity (W/m K)	0.17

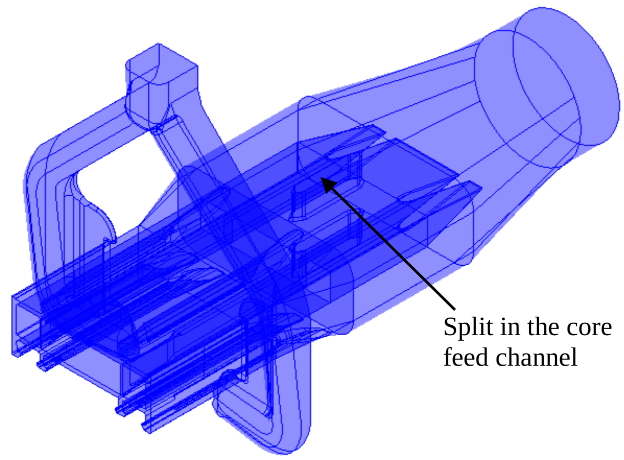

Fig. 1 Geometry of a bilayer die for coextrusion of a window profile.

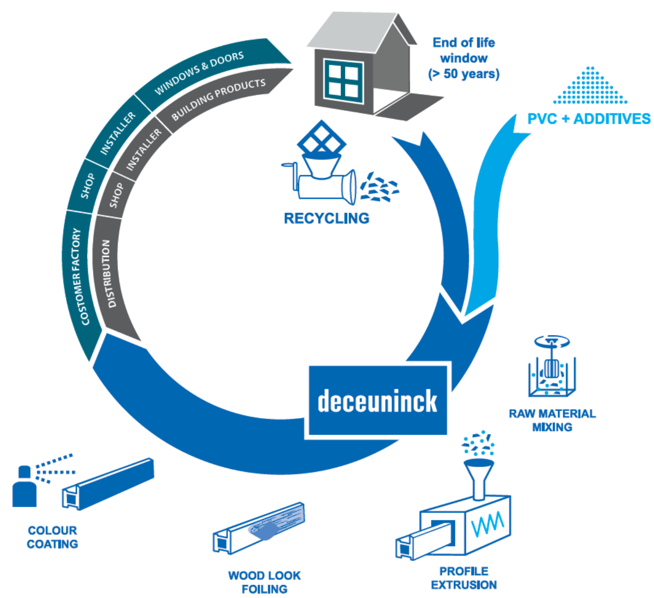

Fig. 2 Closed material loop for PVC at Deceuninck nv.

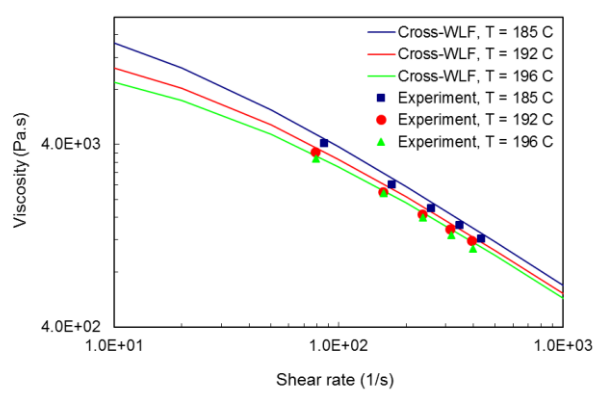

Fig. 3 Shear viscosity data (symbols) and Cross-WLF model fit (curves) to the viscosity data for the PVC resin.

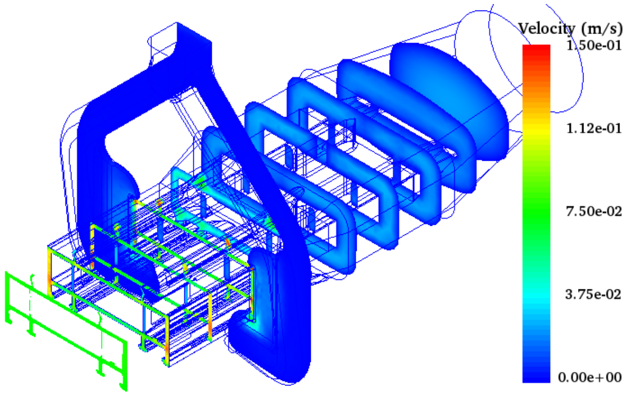

Fig. 4 Velocity distribution in various cross-sections of the coextrusion die.

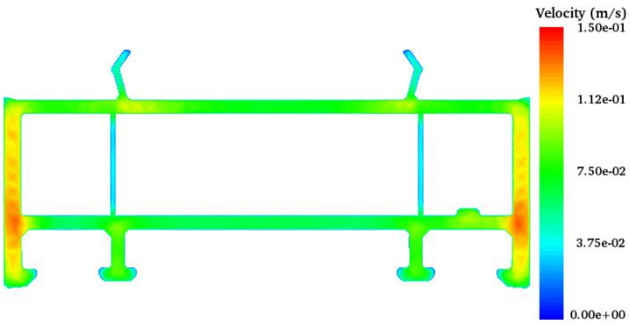

Fig. 5 Velocity distribution at the exit of the final coextrusion die used in production.

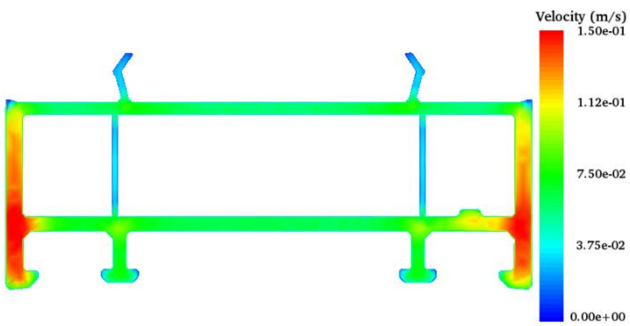

Fig. 6 Velocity distribution at the exit of the initial design of the coextrusion die.

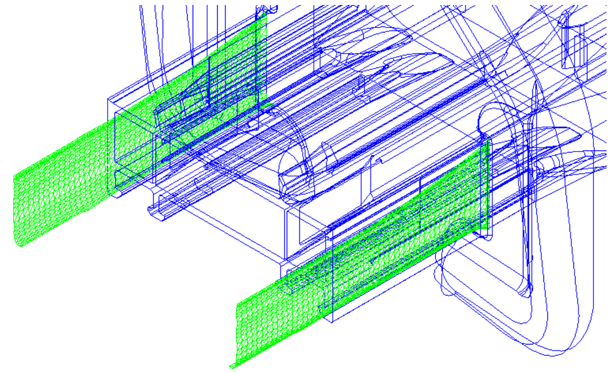

Fig. 7 Interface shape between the two layers as predicted by the mesh partitioning technique.

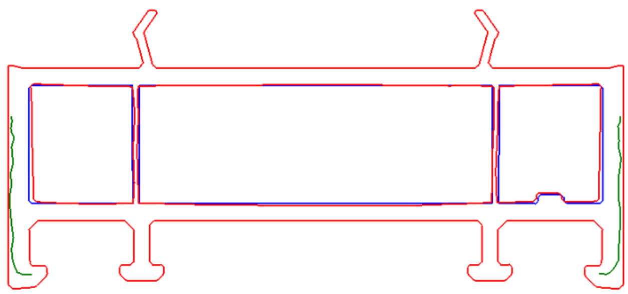

Fig. 8 Predicted shape of the extrudate profile (red) and layer structure (green) at the end of the calibrator. The blue lines show the shape of the profile at the die exit.

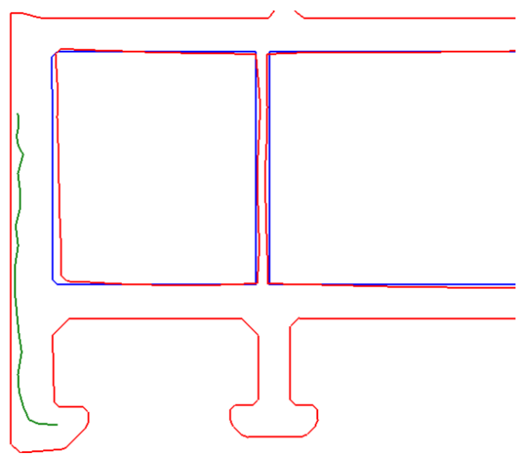

Fig. 9 Close-up of the extruded profile and layer structure.

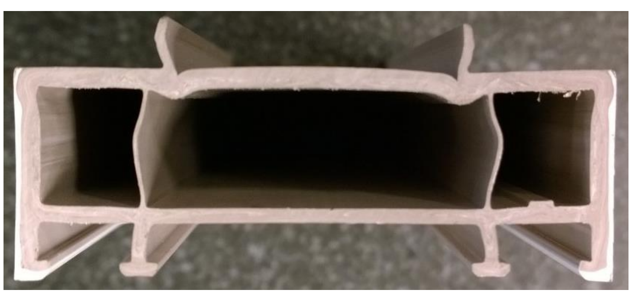

Fig. 10 Shape of the profile and layer structure in the extrusion experiments.

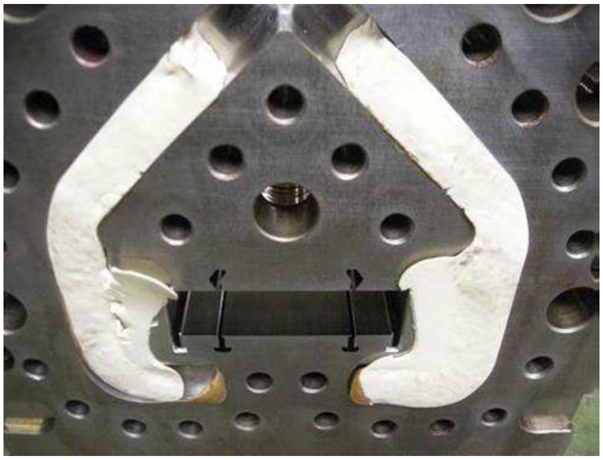

Fig. 11 Degraded polymer near the bottom of the feed channel for the skin layer.

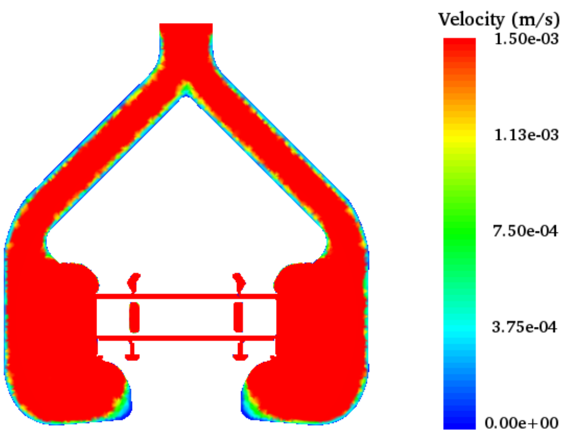

Fig. 12 Velocity distribution showing the stagnant flow near the bottom of the feed channel for the skin layer.

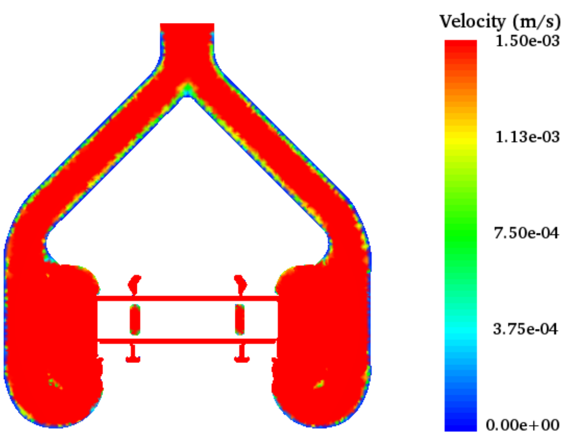

Fig. 13 Velocity distribution with no stagnant flow in the modified feed channel for the skin layer.

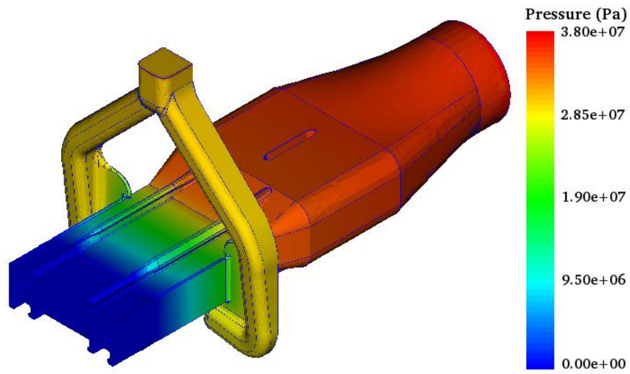

Fig. 14 Pressure distribution in the coextrusion die.

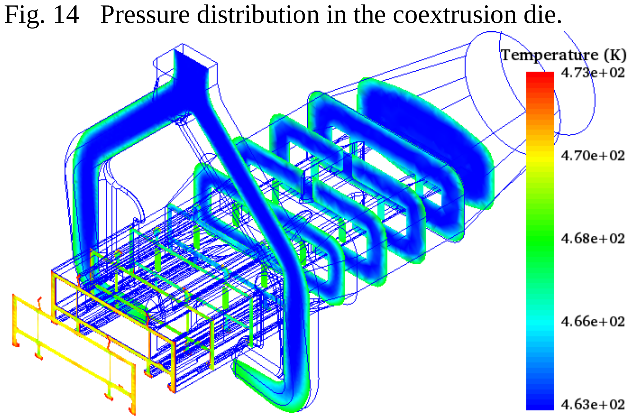

Fig. 15 Temperature distribution in various cross-sections of the coextrusion die.

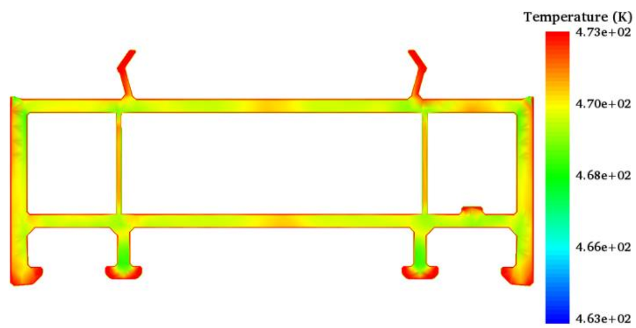

Fig. 16 Temperature distribution at the die exit.

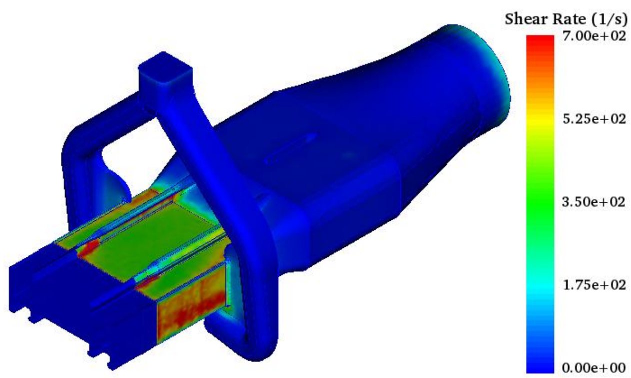

Fig. 17 Shear rate at the die walls.