CAST FILM EXTRUSION DIES OPTIMIZED FOR PFAS-FREE FORMULATIONS

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Abstract

Currently installed cast film extrusion lines commonly employ general-purpose extrusion dies to process multiple resin types across a wide range of throughput rates. Many of these dies rely on nickel-based internal surface plating and fluoropolymer-based polymer processing aids (PPAs) to prevent polymer plate-out and associated optical defects. In response to growing environmental concerns surrounding per- and polyfluoroalkyl substances (PFAS), the use of fluoropolymer-based PPAs is declining. In the absence of PFAS-based PPAs, many conventional cast film dies fail to generate sufficient wall shear stress to suppress polymer plate-out, with the most severe effects occurring near the die ends.

This work demonstrates that purpose-designed, streamlined extrusion die flow-channels—engineered to preserve elevated wall shear stress and incorporating low-surface-energy chrome plating—enable stable processing of PFAS-free formulations without reliance on fluoropolymer-based additives.

Introduction

Flat extrusion dies are used to manufacture thermoplastic products such as cast film, flat sheet, and oriented film, as well as for extrusion coating or laminating processes. The primary function of a flat extrusion die is to uniformly distribute the molten polymer across the width of the die slot. Uniform flow distribution is typically achieved by designing the internal flow-channel geometry so that each flow path experiences a nearly identical pressure drop, as shown in Figure 1. One commonly used flow-distribution channel is called the coat-hanger manifold, named for its characteristic shape [1].

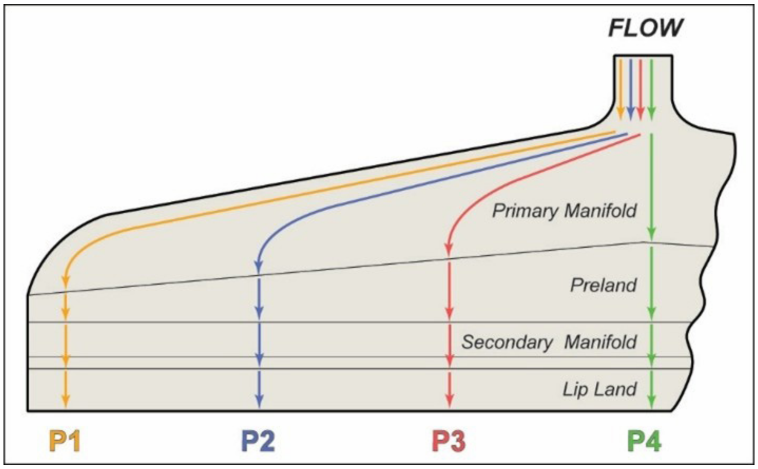

Figure 1: A diagram showing uniform flow distribution through a flat extrusion die channel (P1≈P2≈P3≈P4).

In this design, a centrally fed primary manifold distributes melt laterally towards each end of the die. It is the largest internal cavity within the flow channel, so this chamber tends to have the lowest average polymer velocity. In diminishing-volume manifold designs, the manifold volume decreases towards the ends of the die, increasing melt velocity and reducing polymer residence time. These designs promote improved purging behavior and more effective wall scrubbing compared to general-purpose manifolds with constant cross-section primary manifolds. Downstream of the primary manifold, a pre-land section further equalizes the pressure drop by introducing additional resistance near the die center. While still used in many lower-pressure and mono-layer applications, this classic coat-hanger channel, however, is not ideally suited for cast film applications. Since the layout has an angled backline in the flow channel, the die lips can become distorted (often called "clam-shelling") due to high pressure from the small operating lip gaps, high viscosity levels, and large throughput rates that are typical of a cast film process.

Figure 2 illustrates a common general-purpose cast film extrusion die. This design features a straight manifold backline, which allows uniform mechanical deflection of the die lips under pressure. The primary manifold has a relatively large and constant cross-section, enabling operation across a broad range of polymers and throughput rates. While this flexibility is advantageous, the design suffers from reduced melt velocity near the die ends. When paired with nickel- (or nickel-composite) plated flow surfaces and PFAS-free formulations, this can lead to polymer stagnation and plate-out, requiring frequent cleaning to prevent optical defects (See Figure 3).

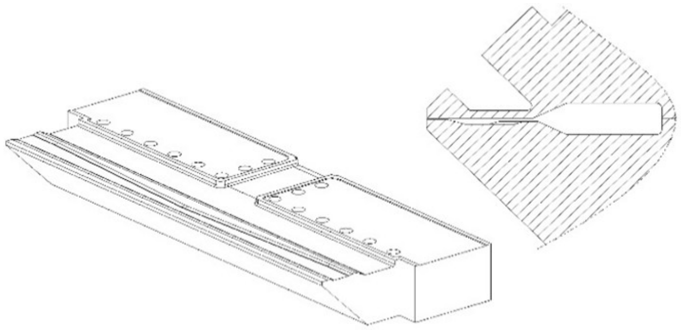

Figure 2: Isometric sketch of common cast film extrusion die (fixed half) with cross-section (Verbruggen image).

Figure 3: Residual degraded material adhered to the flow channel, requiring frequent cleaning to avoid defects.

A modern alternative flow-channel design is shown in Figure 4. This design incorporates a diminishing-volume primary manifold with a straight backline geometry. As the primary manifold cross-section decreases towards the die ends, melt velocity increases, resulting in higher polymer shear stress at the wall surfaces.

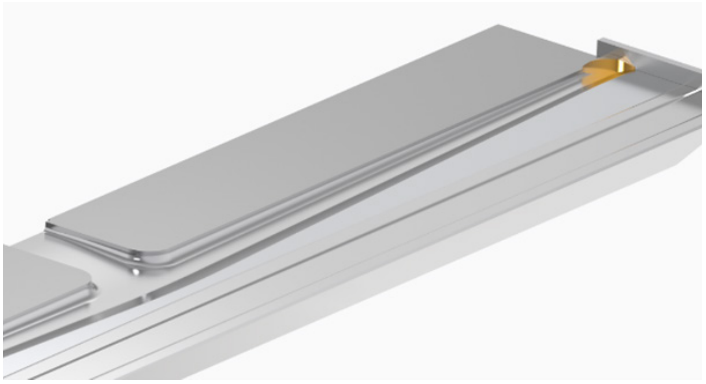

Figure 4: Multiflow™ 10, a patented flow distribution channel with straight manifold backline and diminishing volume primary manifold channel (US Patent 12,558,830 B2).

Shear stress is the normal force acting on the flow channel walls resulting from the flow of the molten polymer. When sufficient shear stress is present, polymer chains adhering to the die wall can be continuously detached, a condition referred to as surface renewal. In practical terms, insufficient surface renewal manifests as gradual plate-out, increasing pressure drop, and the onset of optical defects over time. The shear stress required to achieve surface renewal depends primarily on the surface energy of the flow surface and, secondarily, on the polarity of the polymer being processed. Polar plastics require higher shear stress than non-polar plastics to achieve equivalent wall scrubbing.

Surface renewal in polyolefin extrusion is governed by the balance between wall shear stress and adhesion at the polymer-metal interface. Experimental studies have shown a linear relationship between the critical shear stress for detaching adhered polymer chains and the interfacial work of adhesion, with low-surface-energy die surfaces requiring substantially lower stresses for adhesive failure [2]. Chrome-plated die surfaces exhibit significantly lower surface energies than bare conventional steels, stainless steels, or nickel-plated surfaces, placing typical chrome-plated interfaces in a regime where adhesion breakdown occurs at single-digit kilopascal shear stresses. Accordingly, a wall shear stress on the order of 7 kPa is sufficient to achieve basic surface renewal for neat polyolefins flowing through chrome plated extrusion dies, consistent with prior adhesion-controlled flow instability and die buildup literature.

Figure 5 shows a table comparing the measured surface energy of four flow surfaces (bare AISI P20 tool steel, bare 15-5 PH stainless steel, chrome-plated stainless steel, and nickel-plated stainless steel). In preparation for the testing, all flow surfaces were polished to 0.05 micrometer Roughness Average (Ra) finish level.

	θ_{H_2O} (deg)	$\theta_{CH_2I_2}$ (deg)	γ_s^d (dynes/cm)	γ_s^p (dynes/cm)	γ_s (dynes/cm)
P20S (tool steel)	67.1	50.6	28.4	13.0	41.3
I5-5 HI025 (Stainless Steel)	79.4	55.7	27.3	6.9	34.2
Chrome (on Stainless Steel)	98.4	71.4	20.6	1.9	22.5
Nickel (on Stainless Steel)	68.7	46.3	31.1	10.9	42.0

Figure 5: Table comparing droplet contact angles (for H2O and CH2I2) and surface energies (dispersive component, polar component, and total) for a variety of surfaces.

Note that, in this testing, the nickel-plated flow surface had nearly twice the total surface energy as the chrome-plated flow surface (42.0 versus 22.5 dynes/cm). For polyolefins, which are non-polar plastics, one should consider primarily the dispersive component of the surface energy. The relative dispersive components of the surface energy are 31.1 dynes/cm for nickel versus 20.6 dynes/cm for chrome. If processing neat polyolefins through nickel-plated tooling, the shear stress needed to achieve surface renewal would be (31.1/20.6 x 7 kPa ~ 10.6 kPa).

Historically, fluoropolymer-based PPAs dramatically reduced the effective surface energy of nickel-plated tooling [3]. After sufficient processing time to reach equilibrium, typical PPAs lowered the required shear stress for surface renewal to approximately 5.4 kPa. Figure 6 summarizes these minimum shear stress values to achieve surface renewal. These values define practical minimum wall shear stress targets for stable, self-scrubbing operation. With the elimination of PFAS-based additives, die geometry and plating selection become critical factors in maintaining self-scrubbing flow behavior.

Formulation	Surface Plating	Shear Stress (kPa)
Neat Polyolefin	Chrome	7.0
Neat Polyolefin	Nickel	10.6
Polyolefin+PFAS PPA	Nickel or Chrome	5.4

Figure 6: Minimum shear stresses for surface renewal with neat polyolefins and with polyolefins + PFAS PPA.

Composite platings, such as Ni-diamond, while beneficial for wear resistance, introduce micro-scale surface features that can increase mechanical anchoring of polymer chains. In adhesion-limited, PFAS-free polyolefin extrusion, this effect may increase the critical shear stress for surface renewal relative to smooth nickel-plated flow surfaces.

Flow Simulation Methodology

Computational Fluid Dynamics (CFD) simulations were conducted using Simcenter FlowEFD (Mentor Graphics), a CAD-embedded CFD solver, to compare the performance of two cast film extrusion die designs:

1. A conventional general-purpose flow channel with a constant-volume primary manifold.
2. A modern diminishing-volume primary manifold design utilizing the Multiflow™ 10 flow distribution channel (Nordson Extrusion Dies Industries, LLC, US Patent 12,558,830 B2).

The simulated processing scenario consisted of a 2700mm-wide cast film die producing 25-micron film at a total throughput rate of 1000 kg/h through a 0.8mm die lip gap. The polymer was an LLDPE/PP blend with a melt density of 0.759 g/cm3.

To accurately capture wall shear stress behavior, simulations modeled only the polymer skin layers, which each account for at least 12.5% of the total thickness and remain in contact with most die flow surfaces. The skin layers are the most important to consider when optimizing the design [4]. This approach avoids artificially diluting wall shear predictions that can occur when bulk-averaged velocity fields are used. The practice also accurately predicts both flow uniformity and wall shear behavior for coextruded applications.

Material Rheology

Shear viscosity for the resin is shown in Figure 7 and was modeled using a modified cross as follows:

$$\eta = \eta_o / [1 + (\eta_o \dot{\gamma} / \tau^*)^{1-n}] \quad (1)$$

where η is the shear viscosity (Pa-s), $\dot{\gamma}$ is the shear rate (1/s), and n, η_o, τ^* are model constants. The model constants for the LLDPE/PP blend are provided in Table 1.

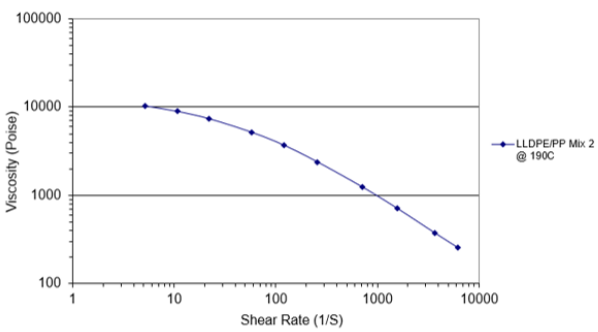

Figure 7. Shear viscosity of LLDPE/PP blend at 190°C.

Results and Discussion

General-Purpose Die

The general-purpose die produced reasonably uniform flow at the die lip exit with a total pressure drop of 94.8 bar (see Figures 8 and 9).

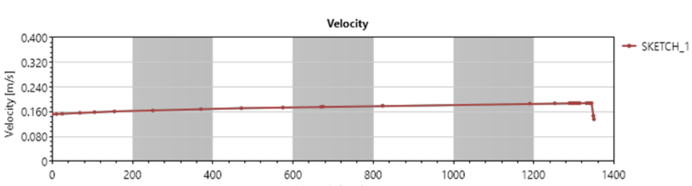

Figure 8: Velocity at lip exit plot for ½ of the die width, where 0 is at the center of the die 1350mm is at the end of the die. This is for the general-purpose cast film die.

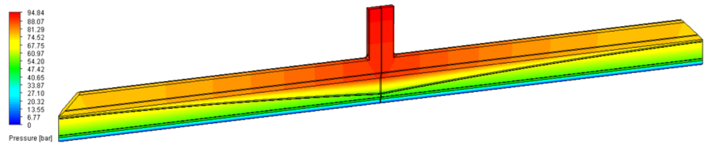

Figure 9: Pressure drop through general-purpose cast film die (94.84 bar).

However, wall shear stress levels within the constant-cross-section primary manifold were insufficient to achieve surface renewal when PFAS-based PPAs were not present. For nickel-plated tooling, only the central third of the die reached the minimum shear stress required for surface renewal (Figure 10), while chrome-plated tooling exhibited sub-critical shear stress near the die ends (Figure 11). These conditions would result in polymer plate-out, optical defects, and frequent cleaning shutdowns when processing PFAS-free formulations.

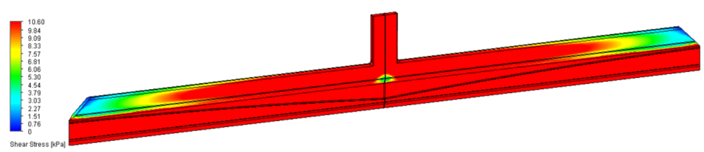

Figure 10: Shear stress plot for general-purpose cast film die with the scale's maximum value capped at 10.6 kPa.

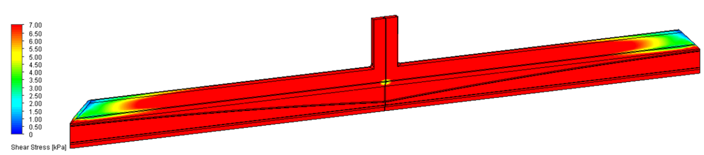

Figure 11: Shear stress plot for general-purpose cast film die with the scale's maximum value capped at 7.0 kPa.

When PFAS-based PPAs were included in the formulation, the required shear stress threshold was reduced, and acceptable surface renewal was predicted across most of the useful die width (Figure 12). This confirms that many conventional general-purpose dies are fit-for-use primarily when PFAS-based PPAs are employed.

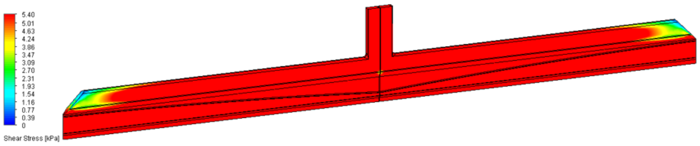

Figure 12: Shear stress plot for general-purpose cast film die with the scale's maximum value capped at 5.40 kPa.

Thus, without PFAS-based PPAs, the general-purpose die's limitations are not related to flow uniformity, but to insufficient wall shear stress in low-velocity regions of the manifold.

Diminishing-Volume (Multiflow™ 10) Die

The diminishing-volume primary manifold design produced uniform flow distribution with a lower total pressure drop of approximately 89.8 bar (Figures 13 and 14).

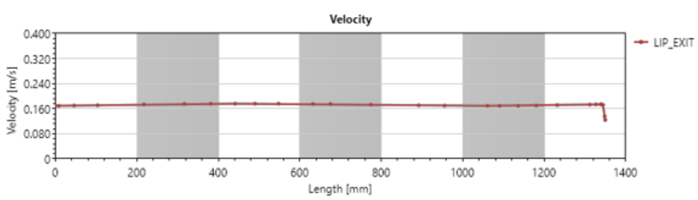

Figure 13: Velocity at lip exit plot for ½ of the die width, where 0 is at the center of the die 1350mm is at the end of the die. This is for the patented Multiflow 10 cast film die.

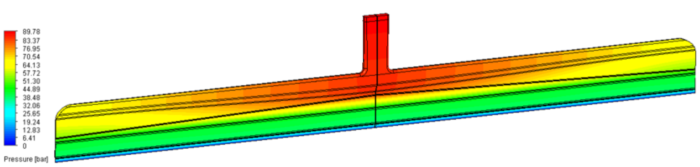

Figure 14: Pressure drop through Multiflow 10 cast film die with diminishing volume primary manifold (89.78 bar).

Elevated wall shear stress levels were predicted across nearly the entire useful flow-channel surface, exceeding 7 kPa in the chrome-plated flow regions responsible for sellable film. Only the extreme manifold endsweep regions exhibited lower shear stress. These low shear-shear regions occur exclusively in the edge trim and neck-in zones and therefore do not impact sellable film quality or run length (Figure 15).

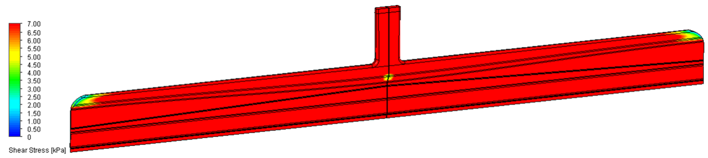

Figure 15: Shear stress plot for Multiflow 10 cast film die with the scale's maximum value capped at 7.0 kPa.

Additionally, polymer streamline trajectory time was significantly reduced near the die ends compared to the general-purpose design, indicating faster purging behavior during material changeovers (Figures 16 and 17).

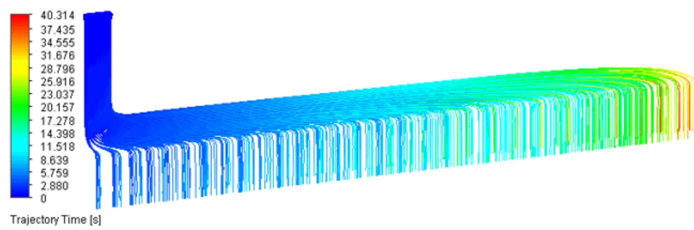

Figure 16: Trajectory time plot for general-purpose cast film die. Times near the ends range near 30 to 40 seconds.

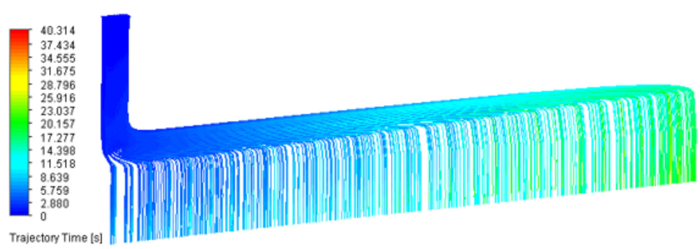

Figure 17: Trajectory time plot for Multiflow 10 cast film die. Times near the ends range near 15 to 25 seconds.

Conclusions

Cast film extrusion dies intended for PFAS-free formulations should incorporate diminishing-volume primary manifolds and low-surface-energy chrome-plated flow surfaces. CFD simulation results demonstrate that the Multiflow 10 flow-distribution channel generates sufficient wall shear stress to promote surface renewal without PFAS-based PPAs, while also reducing overall pressure drop and polymer residence time.

These characteristics enable long, uninterrupted production runs, reduced sensitivity to pressure increases associated with PFAS-free formulations, and improved operational efficiency compared to general-purpose die designs.

As PFAS-free formulations become standard rather than optional, extrusion die flow-channel design will increasingly determine process robustness.

References

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Keywords

Extrusion die design, polymer flow streamlining, surface energy, surface renewal