COMPUTATIONAL DESIGN OF A U-PROFILE DIE AND CALIBRATOR

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Abstract

The objectives of this work are three-fold: 1) to validate that an open profile product can be made using simulation alone to design a die (design rules of thumb are not applied), 2) assess the role of the calibrator in shaping the free surface of the extrudate, and 3) quantify the heat transfer in a vacuum calibrator and assess how such data can be used to design calibrators for other products. The scope of this paper includes: 1) three-dimensional flow simulation to design a die to make a U-shaped extrusion, 2) experimental trials to validate the mass flow balance through the die and the cooling performance of the calibrator, and 3) comparison of the heat transfer data obtained during calibration trials to published data for profile calibrators.

Introduction

Experts in the polymer processing field have cited that the increasing complexity of product designs, coupled with the shorter development times and a shortage of qualified engineers fuel the need for more process simulation in industry [1]. Several commercial polymer flow simulation programs are used for profile die design today [2,3,4,and 5]. However, because the cooling rate of the extruded product determines the speed of the extrusion line, optimal design of a calibrator is critical to productive operations. In addition, the design of the calibrator also has an influence on the straightness of the final product [6] because uneven cooling results in warped products.

Analytical solutions have been developed to aid the design of calibrators for simple shapes such as sheets and pipes [7]. More complex shapes, such as window profiles, require the use of finite element methods that can model arbitrary shapes. Some of the first robust simulation methods for complex extrusion calibrators were developed by Sheehy and coworkers [8]. Other optimization methods for cooling line locations in calibrators were developed by Fradette et al [9].

Simulations depend upon the use of proper boundary conditions, specifically in calibration design: what is the heat transfer between the extrudate and the calibrator? This problem was studied in detail for PVC extrusions in steel calibrators by Fradette et al [10]. In a recent work, Placek and coworkers [11] argue that the uncertainty in the heat transfer between the extruded product and the calibrator affects the reliability of the absolute temperature changes in the profile. However, they claim that approximate values of the heat transfer rate can be used to discern important trends in calibrator design.

The use of simulation for extrusion profile products has three distinct but interrelated areas: die flow, calibrator cooling optimization, and extrudate shape prediction due to thermal shrinkage. This paper will examine how useful simulation can be in the design of extrusion tooling by examining the first two of these three areas: 1) demonstrate how reliably a profile die can be designed using simulation alone, and 2) summarize the cooling performance and shaping behavior of a calibrator. The latter is done to highlight the complexities involved in simulating the calibration process and in coupling die flow with calibrator operation.

Die Design via Simulation

The design process begins with a target product shape. In this work, the product is a U-profile that has a uniform wall thickness of 2.54 mm, is 30.5 mm wide at the base, and 28 mm tall. The objective of the simulation is to determine the die passage that results in a balanced mass flow exiting the die and an extrudate shape down stream of the die that closely matches the target profile. The extruder on which the die is used places an additional constraint on the design: the inlet to the die must be a 25.4 mm diameter circle. A wire frame, exploded view of the stack die made for this study is shown in Figure 1.

A commercial polymer flow simulation program Polyflow was used to design the die passage [2]. Only the passage in the pre-land and die land plates were included in the computational domain. Due to the relatively open passages upstream of the pre-land, it assumed flow through this region has negligible results on flow in the pre-land and land. The shape of the die exit is determined by solving an inverse flow problem where the target profile is given as the down stream shape of the extrudate. The program computes the die exit shape that results in the target profile downstream of the die after melt velocities equalize in the free-surface region. Visco-elastic effects were neglected. The die swell that results is due to the velocity relaxation of the melt as it exits the die.

The product is made of high impact polystyrene (HIPS). The thermal and rheological parameters of the HIPS are given in Table 1. A Cross/WLF viscosity model is used to characterize the temperature and shear rate dependence of viscosity.

Finite Element Model

Due to the symmetry of the die, only one-half of the passage is modeled as shown in Figure 2. The finite element model consists of 16,592 hexahedral elements and 19,530 nodes with the following boundary conditions:

- Fully developed inlet velocity (mass flow of 5 kg/hr),
- Uniform inlet temperature = 232 °C,
- No slip at the die wall,
- Zero pressure and zero traction at the free surface boundary.

Simulations were run on a Windows PC with 1 GB RAM and a 2.39 GHz processor. On this platform, a converged isothermal analysis required 552 minutes of CPU.

Simulation Results

The inverse simulation of the die and free surface flow exiting the die, results in a die lip geometry that is distorted compared to the target profile as shown in Figure 3. Also shown in this figure is the profile of the inlet to the pre-land plate that was determined by a series of trial and error extrusion simulations to insure a balanced mass flow exiting the die. The simulated mass flow exiting the die was uniform to within 5 percent with the ends of the U being almost 10% less than the average. Plots of the pressure distribution and velocity magnitude through the die are shown in Figure 4. As the melt exits the die the velocity gradients relax due to lack of boundary traction to form the extrudate in the target shape.

Experimental Procedure

Nodal data at distinct sections along the flow path was used to fabricate the die plates via wire EDM. The computed profile of the die exit was burned straight through the die land plate. A linear interpolation of the pre-land contour and the die land contour was burned in the pre-land plate.

Calibrator Design

Conventional design rules for calibrators would dictate the calibrator opening to be a small percentage larger than the target product profile. The intent of this work, however, was to make a calibrator the size of the simulated free surface extrudate. The problems encountered in making a properly sized product were compounded by the shape of the target product. Unlike hollow profiles, the U-shaped profile tends to shrink onto the core of the calibrator. This shrinkage can generate large frictional forces that can lead to retarded movement through the calibrator and thus blockage to incoming melt. A hollow profile shrinks and pulls away from the calibrator, thus tending to minimize blockage problems.

The calibrator consisted of an upper and a lower portion as shown in Figure 5. Both halves had vacuum slits and cooling lines. The units were made by machining individual plates and bolting them together. The calibrator was run as a dry vacuum calibrator. Upon exiting the calibrator, the extrudate enters a cooling tank for additional cooling in a water bath.

Extrusion Trials

Due to the relatively low hot melt strength of Styron 478 for profile extrusion (Melt Flow Index=6), a lower melt HIPS was used for the extrusion trials (BASF 496N, MFI=2.8)

- Melt temperature of 232 °C
- Die temperature of 232 °C
- Mass flow rate varied to assess changes in heat transfer.

The extrusion trials were conducted on a Brabender Plasticorder lab scale extruder with a 0.019 m (0.75 in) 25 L/D screw. The die pressure at the midpoint of the transition plate was recorded with a Dynisco PT 4626 melt pressure transducer. The U-profile was extruded “up-side down” so the extrudate would not pool stagnant water as it passed through the cooling tank. A schematic of the calibration/cooling set-up is shown in Figure 6. The calibrator ran as a dry vacuum calibrator with 8 inches of mercury vacuum. Line speeds of the extrudate were controlled by a Gatto model 202-3D puller. The actual line speed was recorded by noting the time required for a mark on the extrudate to pass through a distance of 30.5 cm.

To quantify the cooling rate of the extrudate as it passed through the calibrator**,** thermocouples were embedded in the upper and lower calibrator halves to within 1 mm of the calibrator/extrudate interface. In addition, three Raytek MID infrared pyrometers were used to measure the temperature of the extrudate entering the calibrator and leaving the calibrator. The temperature of the extrudate on the bottom of the “U” and on the inside of the “U” were measured. This quantifies the cooling performed by the upper and lower calibrators, respectively.

The mass flow uniformity exiting the die was determined by measuring the thickness of the extrudate as it was extruded onto the lower calibrator surface with the upper calibrator removed. No puller was used. The lower calibrator surface forms the inner sides of the “U” and is 25.4 mm wide and 25.4 mm high. During the data collection, the calibrator was run under a slight positive pressure so the extrudate would glide over a cushion of air.

Extrusion Results

Thickness measurements shown in Figure 7 reveal that the die flow is not perfectly balanced. The regions at the end of the U are approximately 10% thinner than near the center, which corresponds to the simulated deficit of mass flow leaving the die lip. Apparently, the swelling after the die did not rearrange the material to achieve a uniform thickness. A perfect extrusion profile would have uniform thickness values at all points measured equal to 2.54 mm, or 100% on the graph. Data denoted by mass flow only are the result of extruding onto the lower calibrator alone: no calibration. Data denoted with a "P" are calibrated products that were made while feeding the calibrator as full a practically possible before choking the inlet. Data labeled "P @ 3 kg/hr" illustrates that a calibrator can redistribute the melt since the trend observed in the other data is to starve the edges at points "A" and "I" in the photograph. The discrepancies between what was measured versus the simulation can be attributed to 1) inaccuracies in the fabricated die, 2) errors in the viscosity model, and/or 3) neglect of visco-elastic melt properties.

The heat transfer data is summarized in Figure 8. The data is presented in terms of Fourier number, a dimensionless parameter proportional to the extrudate contact time with the calibrator and inversely proportional to the square of the extrudate thickness. This format permits ready comparison of different extrusion rates. The procedure to obtain calibrator heat transfer coefficients from the thermocouple and infrared pyrometer data involves using a one-dimensional, transient finite element model. The model simulates the cooling of the extrudate with unique convection coefficients (which could also be modeled as contact resistance heat transfer coefficients) and ambient temperatures on either side. The thermal properties in Table 1 were used to model the cooling extrudate. The infrared temperature measurement of the extrudate upstream of the calibrator was used as the initial temperature of the melt. The upper and lower calibrator temperatures were used as the respective ambient temperatures. The infrared temperature readings of the extrudate exiting the calibrator were used as the target temperatures to guide the proper selection of the upper and lower calibrator convection coefficients.

The lower calibrator exhibits a greater heat transfer rate with the extrudate than the upper unit. This is not surprising since the extrudate tends to shrink onto the lower calibrator unit. Notably, the heat transfer values obtained in this work are an order of magnitude lower than those obtained by Fradette et al [10] although both experiments involved dry vacuum calibrators.

Conclusions

Profile extrusions designed by simulation alone will require some trial-and-error adjustments. The wall thickness distribution of an extrudate leaving the die can be adjusted by the calibrator. Calibrator heat transfer values are dependent upon the calibrator geometry and the degree of feeding into the calibrator. Comparison to other published calibrator heat transfer data suggests cooling rates may not be generalized for use in new calibrator designs. As other researchers have indicated [7,10, and 11], calibration design can be done only to estimate the cooling performance, not predict absolute cooling rates.

References

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Key Words

profile die design, profile calibration,
CFD, experimental verification

Table 1 Thermal and Rheological Properties

Material	HIPS
Grade	DOW Styron 478
Thermal Properties	
Melt Density [kg/m^3]	875.
C_p [J/(kg-C)]	1816.
K [W/(m-C)]	0.133
Rheological Properties	
Viscosity model: Cross-WLF	
n	0.2947
τ^* (Pa)	3.1165E+04
D_1 (Pa-s)	5.623E+12
D_2 (K)	373.
A_1	30.2
A_2 (K)	51.6

$$\eta(T,\dot{\gamma}) = \frac{\eta_0(T)}{1+\left(\dfrac{\eta_0(T)\,\dot{\gamma}}{\tau^*}\right)^{1-n}}, where$$

$$\eta_0(T) = D_1 \exp\left[-\frac{A_1(T-D_2)}{A_2+(T-D_2)}\right]$$

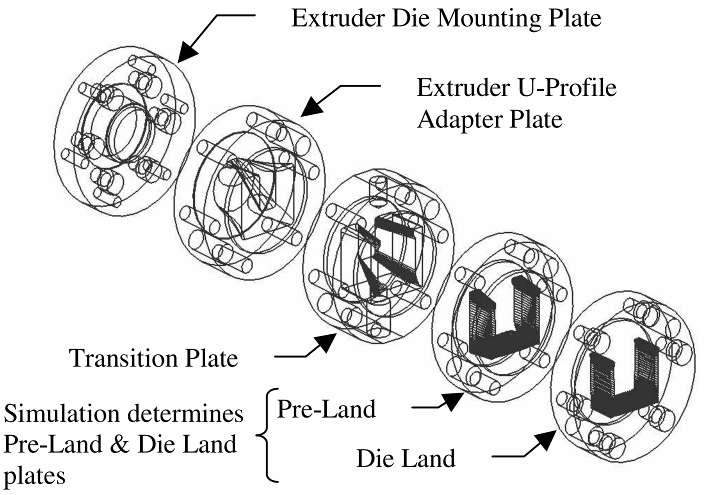


Figure 1. U-Profile Stack Die

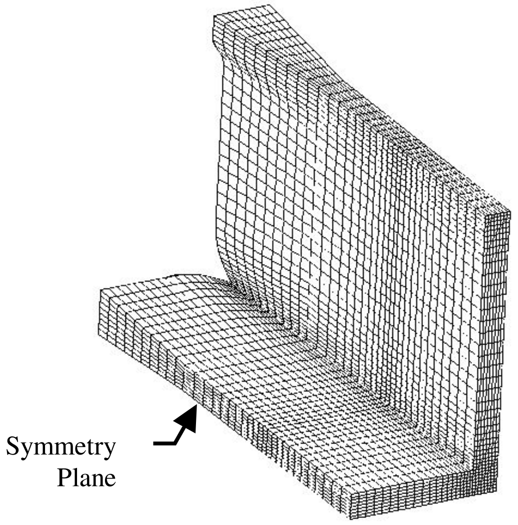


Figure 2. Finite Element Model of Die Passage & Free Surface

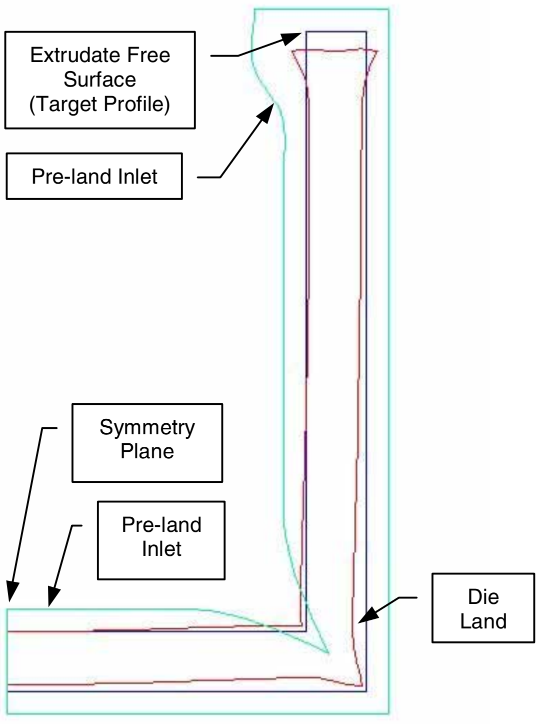


Figure 3. Contours of Pre-land, Land, and Extrudate

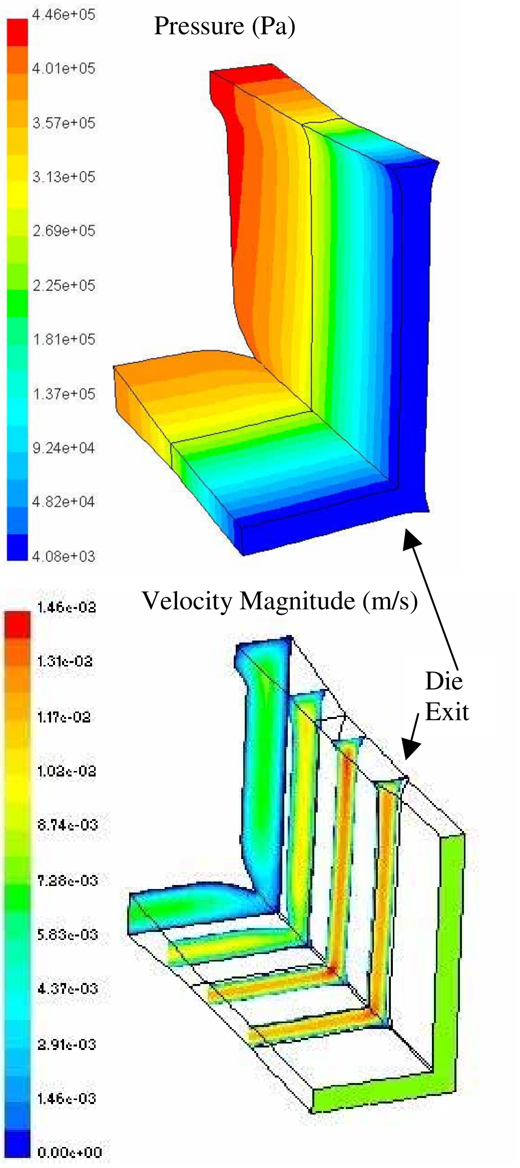
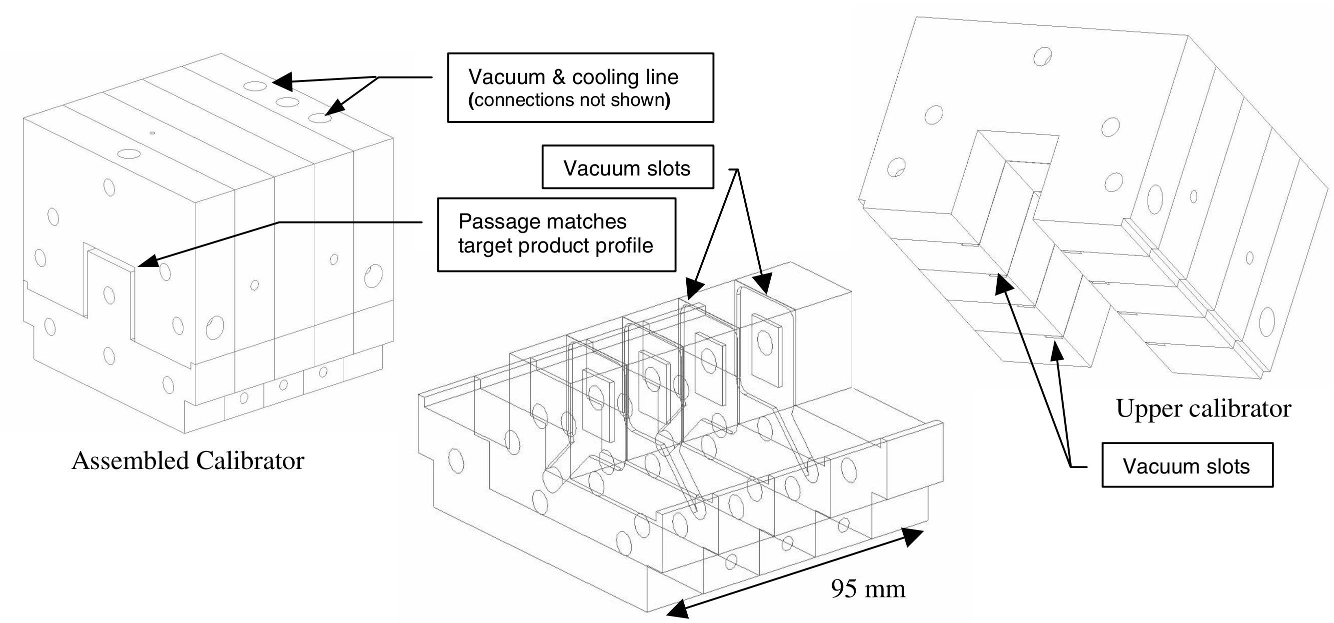


Figure 4. Pressure and Velocity Simulation Results



Details of vacuum slots and cooling lines in lower calibrator

Figure 5. U-Profile Calibrator Design

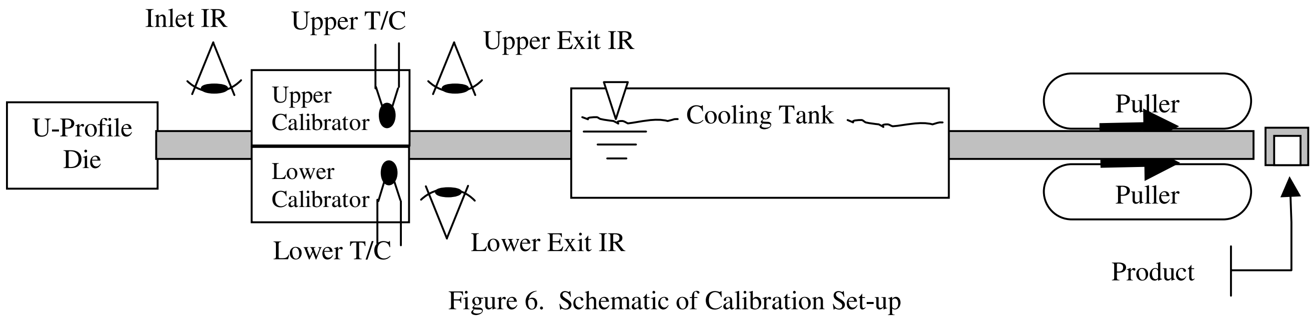


Figure 6. Schematic of Calibration Set-up

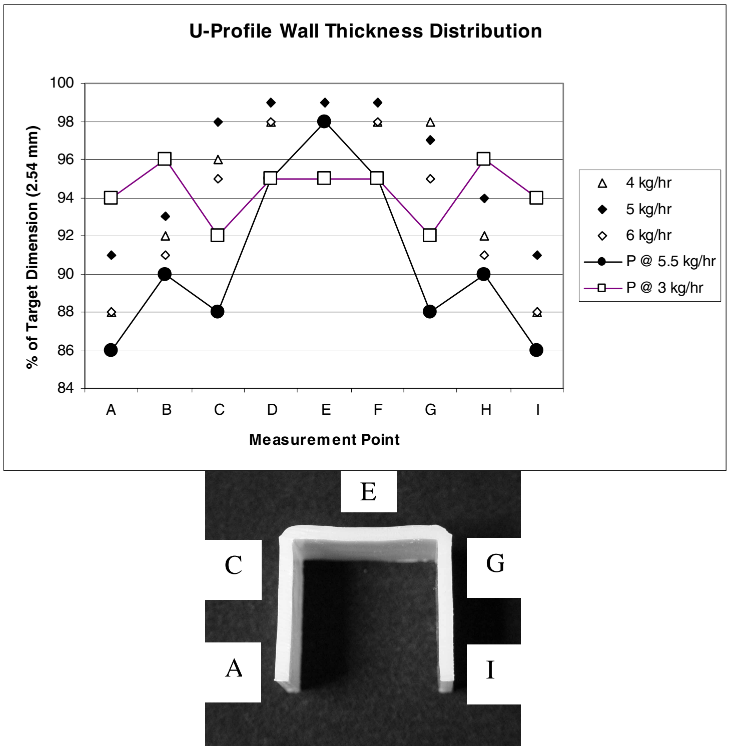


Figure 7. Product "P @ 3 kg/hr" Photograph and Profile Data

Representative U-Profile Calibrator Heat Transfer Data				
Recorded temperatures for P @ 3 kg/hr (C)				
Inlet IR	Upper IR	Lower IR	Upper T/C	Lower T/C
206	71	60	30	24
Contact time with calibrator: 15 sec.				
Thickness of extrudate between IR probes: 2.34 mm				
Fourier number = 0.93				
Estimated heat transfer coefficients (W/m^2/K)				
	h_upper = 175			
	h_lower = 225			

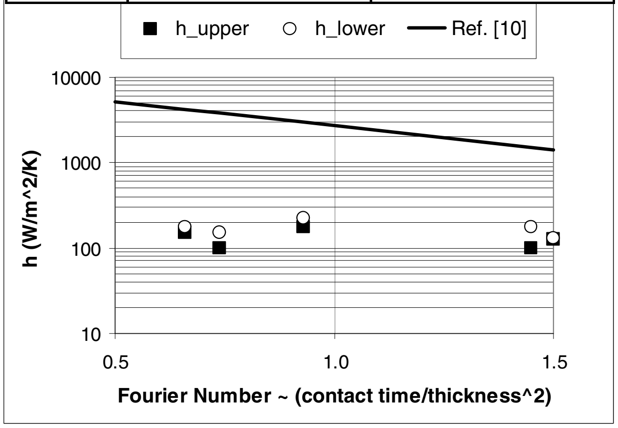


Figure 8. Comparison of Heat Transfer Data