THE INFLUENCE OF DESIGN AND PROCESSING PARAMETERS ON THE MIXING PERFORMANCE OF A FLUTED MIXER

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Abstract

In this paper, the mixing efficiency of two slightly different fluted mixing elements is studied. RGB spectral analysis is used for the quantification of the mixing. The overall mixing appears to be equal after sufficient mixing time. The mixer without the wiping flight, however, creates a stagnation layer of material which rotates between the mixer and the barrel. This layer is characterized by a long residence time. The residence time of the layer is twice as long as for a mixer with the wiping flight. The long residence time is again measured by RGB spectral analysis and also visualized in the video. The results of a 3D FEM simulation shows that the mass flow rate of the stagnation layer represents almost 50% of the total mass flow rate.

Introduction

Mixing is a very important process in single-screw extrusion. Achieving good mixing performance, under specified processing conditions, is a key requirement to obtain a uniform and homogenous mixture. So, it is not surprising that considerable effort is spent on analyzing different types of "mixing elements", "mixing heads" or "mixing sections" in single-screw [1-6] and also twin-screw [7-13] extrusion. In principle, there are two basic mixing mechanisms. Dispersive mixing is based mainly on reducing the size of mixture components by shear or elongational stress. The second one is distributive mixing that redistributes particles throughout the volume [14].

A fluted mixing element, also known as the Maddock mixer [15], is one of the most often examined dispersive mixing sections in extrusion. Almost forty years ago, Tadmor and Klein [16], studied certain designs of fluted mixing sections and proposed a model for calculation of pressure development through the fluted mixing section. Tadmor et al. [17] later improved the model by using the Flow Analysis Network method. Esseghir et al. [18] carried out a detailed comparative study of three different single-screw mixing elements including the Maddock mixer section.

Han and Lee [19] experimentally and also numerically investigated the flow in the Maddock mixer. Their work focused mainly on pressure drop and pressure rise through the mixer. Their results clearly concluded that pressure was generated, under specific processing conditions, and therefore drag flow was predominated over pressure-driven flow. In their work, only 2D analysis was used to compute simulation results and the mixing performance of the Maddock mixer section was not evaluated.

In this work, the evaluation of the mixing performance using the Red-Green-Blue (RGB) spectral analysis is presented. The study is focused on color dispersion of the material extruded by two general purpose screws having slightly different fluted mixing sections. The "Closed" design has alternating "shearing" and "wiping" dams (or flights) while the "Open" design is completely undercut so that there are no "wiping" dams. It can be seen that the "Open" design is easier to manufacture and many people assume that this geometry change has little, or negligible, impact on its overall mixing performance. To investigate this assumption, experiments, comparing these two fluted mixer designs, have been performed. A three dimensional Finite Element Method (3D FEM) simulation is also used to help analyze and better understand the fluted mixing element flow field.

Methods

Two general purpose screw designs were prepared for this experiment. The basic screw dimensions are summarized in Table 1.

Table 1. Basic screw dimensions

Total length	28D	Channel depth [mm] Beginning	End
Solids conveying zone	4D	6	6
Melting zone	13D	6	2
Metering zone	2D	2	2
Mixing section	2D	**Fluted mixer**	
Metering zone	7D	2	2

The only variation between these two screw designs is the mixing section where two slightly different fluted mixing elements were used, as shown in Figure 2. Both mixers had three pairs of channels. The shearing gap width was 9.5 mm, its depth was 0.4 mm and a radius of each channel was 7.2 mm. The length of the shearing gap was 80 mm.

The "Closed" mixer has separated pairs of inlet and outlet channels with a shearing gap in between. The wiping flight prevents material flow and cleans the barrel surface.

The "Open" mixer has undercuts from both sides of each channel. Thus, the material is not wiped from the barrel surface. The melt can also enter the channel from the side and not only from the inlet. Therefore, part of the melt can continuously flow in the gap between the mixer and the barrel.

Experiments were done on a special extrusion line with a barrel having several glass windows which are alternately placed on both sides of the barrel as shown in Figure 1. This allowed observation of the polymer melt along the extrusion line from the solids conveying zone to the metering zone. Dimensions of each window were 90x10 mm and the internal diameter of the barrel was 40 mm.

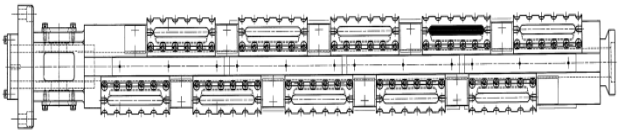


Figure 1. Barrel sketch

The mixer was positioned to be visible through the glass window (black window in Figure 1). The open and closed mixer configurations are shown in Figure 2.

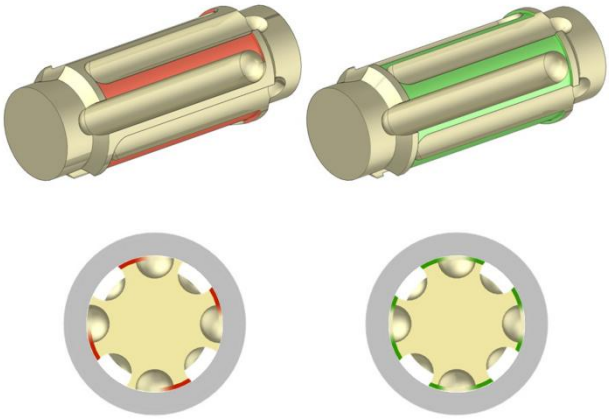


Figure 2. "Closed" (right side) and "Open" (left side) mixer configurations

The output of the extrusion line was connected with a small flat die followed by a system of chill rolls to obtain a uniform film. All experiments were continuously recorded by a video camera which was set on a tripod. Experimental processing conditions are given in Table 2.

Table 2. Processing conditions

Extrusion Line Heat Zones Temperature [°C]				
Zone 1	**Zone 2**	**Zone 3**	**Zone 4**	**Die**
110	230	250	250	250
Mass Flow Rate [kg/hr]				
Screw speed [RPM]		**7**	**14**	**21**
"Closed" mixer		1.24	2.43	3.6
"Open" mixer		1.23	2.37	3.5

Material

The main material used for the study was Hi-Zex 6300M HDPE. Rheological properties were measured on a laboratory grade twin-bore capillary rheometer (Imatek R6000 [20]) with ϕ1x16mm long die and ϕ1×0.25mm short die. Viscosity curves are shown in Figure 3.

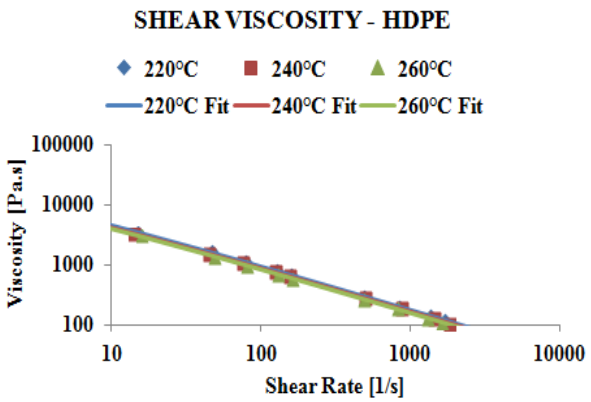


Figure 3. Viscosity curves of HDPE

The rheological data were fitted by the well known Carreau-Yasuda model, in which the viscosity dependence is decribed by the following equation:

$$\eta(\dot{\gamma},T)=\frac{\eta_0 f(T)}{\left[1+\left(\lambda\sqrt{II_D}\,f(T)\right)^a\right]^{\frac{1-n}{a}}} \qquad (1)$$

Where η_0 is the zero shear viscosity, *a*, *n*, λ are constants, *T* is temperature and II_D stands for the second invariant of the deformation rate tensor. The material temperature dependence *f(T)* is exponential and is given by an equation:

$$f(T)=e^{-b(T-T_r)} \qquad (2)$$

The parameter *b* represents the temperature sensitivity and T_r is the reference temperature. The Model variables are presented in Table 3.

Table 3. Carreau-Yasuda Model parameters

HDPE – Model Variables			
Rheology		**Thermal Properties**	
η_0 [Pa.s]	48684	**ρ [kg/m^3]**	770
n [-]	0.1		
λ [s]	0.1171	**Cp [J/(kg.C)]**	2250
a [-]	0.2542		
T_r [°C]	204	**λ [W/(m.K)]**	0.25
b [1/°C]	0.0191		

A LLDPE based, green masterbatch was used for visualization and mixing performance analysis.

Experimental

The experiment was focused primarily on the mixing performance of the fluted mixing elements. To avoid blending errors, clear HDPE was pushed through the extrusion line until the hopper was almost empty. Next, a certain amount of the colorant (about 60g) was added to the hopper to a 2 cm layer. This layer of colorant was followed by a new layer of clear HDPE of the same volume. By this method, five distinct layers in order colorant – HDPE – colorant – HDPE – colorant were prepared. Each new layer was always added after the previous layer had completely left the hopper. A screw speed at 21 RPM was used to run this experimental procedure.

The moment when the first colored particles appeared at the end of the extrusion line was the starting point of the measurement. Then, samples of the flat film were cut to see interactions between the clear and colored regions of the polymer. Thus, this experimental part provides some indication about the speed of the mixing process. All experimental parameters were identical for both mixing sections. These samples were later analyzed in a professional Canon scanner. The scanner light was strong enough to reveal the mixing patterns of the samples. Hi-resolution tiff format pictures were prepared for further analysis. All samples were 3x8 cm. Color pictures of scanned samples were studied in special program routine where the statistics of simple pixels were evaluated. Some examples of the scanned flat film samples for the "Open" and "Closed" mixer are presented in Figure 4 and 5, respectively.

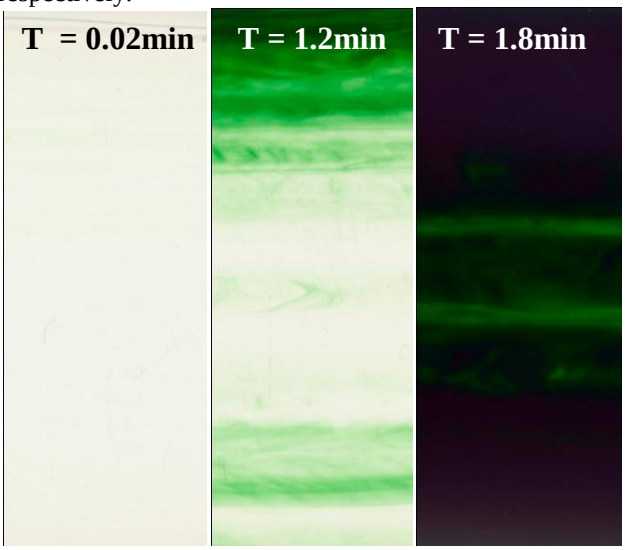


Figure 4. Film samples in different extrusion times by using the "Open" mixer

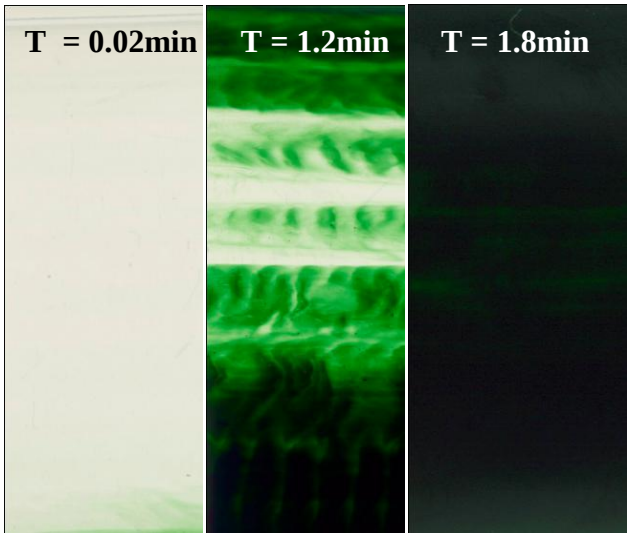


Figure 5. Film samples in different extrusion times by using the "Closed" mixer

Then, an average value of RGB spectra and its deviation was obtained for each pixel. The average value of RGB spectra μ is described by the following equation:

$$\mu = \frac{1}{MN}\sum_{i=0}^{N}\sum_{j=0}^{M} d_{ij} \qquad (1)$$

Where *M*, *N* represents the number of pixels of the sample and d_{ij} stands for the RGB value of the relevant pixel. d_{ij} was taken in each pixel as an average of three RGB values:

$$d_{i,j} = \frac{R_{i,j} + G_{i,j} + B_{i,j}}{3} \qquad (2)$$

RGB color components of a pixel range values from 0 ({0,0,0} black) to 255 ({255,255,255} white). Thus, the material without any additives, pure polymer melt, has a high mean value of RGB. On the other hand, the dark material with added colorant had to have a low mean value of RGB. The degree of brightness, in between the low and high mean value, represents the degree of mixing. The value of the unmixed regions is the deviation of average RGB color. The deviation of the average RGB spectra was calculated by the equation:

$$\sigma^2 = \frac{1}{MN}\sum_{i=0}^{N}\sum_{j=0}^{M} {d_{ij}}^2 - \mu^2 \qquad (3)$$

Where *M*, *N* represents the number of pixels of the sample and d_{ij} stands for the RGB value of the relevant pixel and μ is the mean value of RGB color. The average RGB value reduces as the colorant is added into the process until the mean value of RGB reaches a steady state. The transition from the pure polymer to its colored form is detected by an increase of the deviation of RGB.

The results of RGB spectral analysis equations of the mixing performance can be seen in Figure 6.

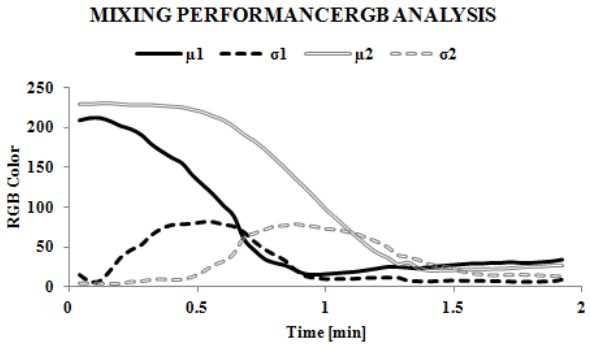


Figure 6. RGB analysis of the mixing performance
1 = Closed mixer, 2 = Open mixer

As shown in the figure, both curves of the average RBG spectra started above 200, which meant that they both were close to the white color with a minimum amount of the green colorant. The decreasing trend of both curves had a similar slope, but the "Closed" mixer (μ1) reduced sooner than the "Open" mixer (μ2). The difference between the "Open" and "Closed" mixer was about 0.4 minutes. Furthermore, the final, steady state RGB value for each mixer is very close. This means that both mixers can provide similar mixing levels, given sufficient time.

The absence of the wiping flight allowed the formation of a layer of the slowly moving material which was rotating close to the barrel surface. The second experimental method was then focused on the behavior of this layer. Probably the most significant variable to characterize the behavior of this layer was the residence time. Thus, one layer of colorant followed by the pure polymer was again added into the almost empty hopper.

A low screw speed of 7RPM was intentionally used to clearly see the layer behavior. Samples of the flat film were again cut, in ten minute intervals, to calculate the mean value of RGB of the polymer. The transition from pure polymer to maximum color and back to the pure polymer also gave a residence time of the flow field. Samples were again evaluated with the RGB spectral analysis.

The RGB curves of the residence time of the "Closed" (μ_1) and "Open" mixer (μ_2) are displayed in Figure 7.

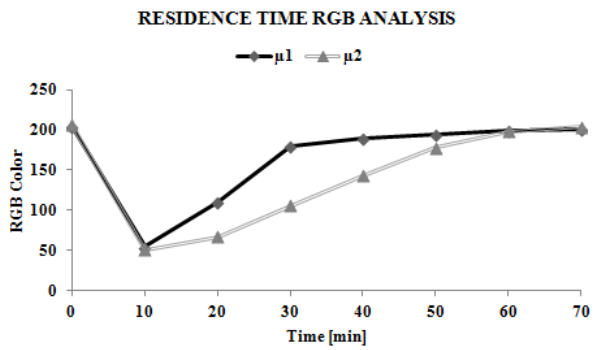


Figure 7. Residence time RGB analysis
1 = Closed mixer, 2 = Open mixer

As can be seen, in Figure 7, the RGB curve started from pure HDPE at time zero and after ten minutes, the minimum RGB value green color was obtained. The first ten minutes was sufficient time for both mixers to achieve the same level of mixing. Then, the amount of green colorant gradually reduced with each new sample taken from the system. These results show that the "Closed" mixer resulted in faster purging than the "Open" mixer and returned close to its initial RGB value after forty minutes versus seventy minutes with the "Open" mixer. The longer purging time, of the "Open" mixer, was due to the presence of the slowly rotating layer rotating in the gap region. This layer was difficult to purge out because of the absence of the wiping flight. The layer was still clearly visible after ninety minutes but its effect on the product color was negligible by this time. The experiment was recorded to help visualize the rotation of the material in this layer**.** The long residence time of the layer could certainly influence the final quality of the due to polymer melt degradation. Furthermore, this layer would also affect the heat transfer from the melt to the barrel surface.

Screen captures from the video, comparing the color change in between the "Open" and "Closed" mixers are shown in Appendix 1.

Simulation Results

The slow, moving layer in the "Open" fluted mixer configuration was further investigated by 3D FEM simulation. A 3D FEM grid, of the mixer geometry, was generated with the fluted mixer template in the Virtual Extrusion Laboratory (VEL™) software [21]. To help ensure high accuracy, quadratic, 27 node, brick elements were used. The grid was constructed from 16,512 elements for the "Closed" mixer flow domain and 17,792 elements for the "Open" mixer. The periodic nature of the geometry allowed for the analysis of only 1 pair of channels. The 3D FEM grid is displayed in Figure 8.

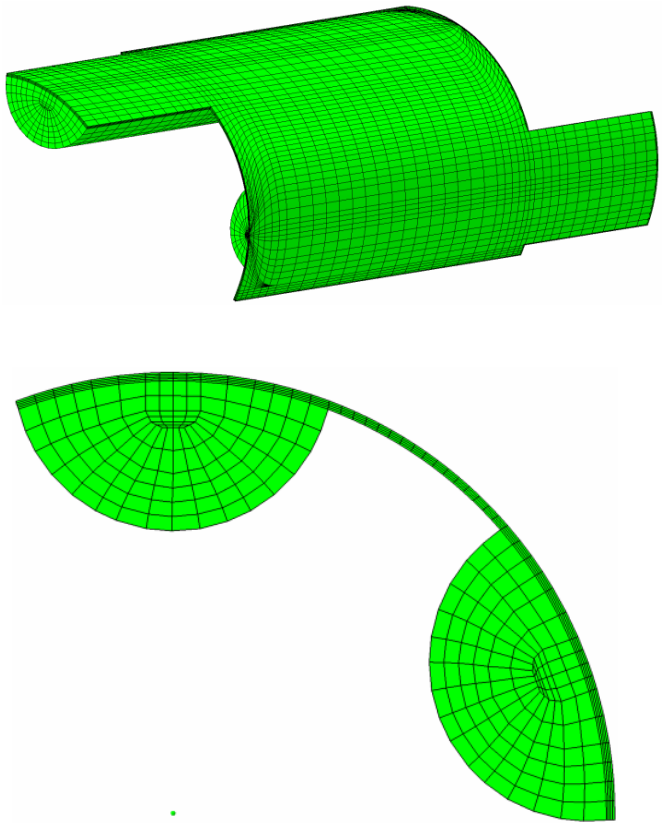
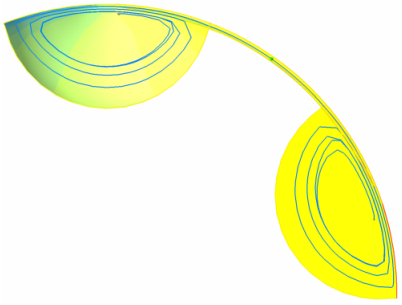


Figure 8. 3D FEM grid

The flow behavior was analyzed with over 60 particle pathlines. Some typical pathlines, which are representative of the flow behavior in the "Open" and "Closed" mixer, are depicted in Figures 9 and 10.

The "seed" location of the pathline was placed in center of the shearing gap, in the middle of the mixer. The same "seed" point was used for both the "Open" and "Closed" mixer. However, the "Open" mixer had a second pathline from a "seed" at the center of the second undercut, as well.



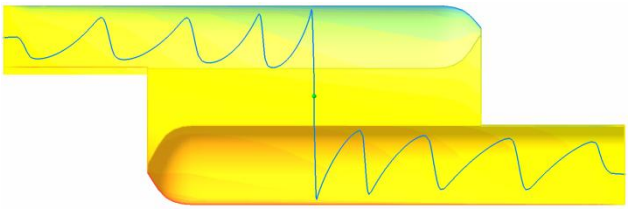


Figure 9. Typical Pathline in the "Closed" mixer

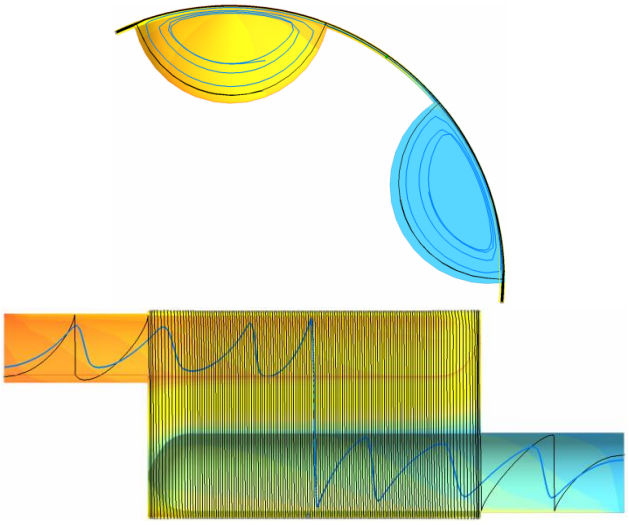


Figure 10. Typical pathlines in the "Open" mixer

It can be seen, from figure 9, that the "Closed" mixer resulted in the pathline making only one pass through the shearing gap while Figure 10 show a pathline making many rotations in the gap region. This represents a high residence time layer near the barrel surface. This layer is created because of the absence of the wiping flight. Surprisingly, the layer fully filled the whole second undercut channel. Then, the layer was squeezed above the deep channel of the mixer and remained near the barrel through the shearing gap and the other deep channel before it reached the opposite undercut.

The squeezing of the layer is due to the rotation of the material flowing from the inlet channel. Interestingly, the mass flow rate of this layer was found to be constant throughout the gap region essentially forming two almost separate, independent flows inside of the "Open" mixer. The mass flow rate over the second undercut was found to be about 50% of the overall mass flow rate coming from the inlet channel. The results are given in Table 5.

Table 5. Mass flow rate of the layer

RPM	Mass Flow Rate [kg/hr]		
	$\dot{m}_{2nd}$	$\dot{m}_{in}$	$\dot{m}_{2nd} / \dot{m}_{in}$
7	0.18	0.42	0.44
14	0.40	0.80	0.51
21	0.60	1.20	0.50

The residence time of this layer, estimated by the 3D FEM simulation, was also much longer than the overall residence time of all other pathlines. The average residence time calculated from more than sixty pathlines in the "Closed" and "Open" mixers was similar. The residence time of some typical pathline in the layer was found to be at least ten times longer than the average residence time of the mixers. Average and layer residence times, at three screw speeds are shown in Table 6.

Table 6. Calculated residence times

RPM	Average RT [min]		Layer RT [min]	
	"Closed"	"Open"	"Closed"	"Open"
7	1.21	1.29	-	13.33
14	0.64	0.68	-	6.01
21	0.43	0.45	-	5.58

Tables 5 and 6 indicate that about 50% of the material flowing in the "Open" mixer has a much larger residence time. This effectively results in the "Open" mixer having a longer average residence time but also a much broader residence time distribution; both of which, may result in degradation problems for some polymers.

Conclusions

RGB spectral analysis was used to quantify the speed of the mixing process for the "Open" and "Closed" fluted mixers. The "Closed" mixer showed a transition from the pure polymer melt to fully mixed that was 0.4 minute faster than the "Open" mixer. However, the overall, final mixing performance of both fluted mixer designs appears to be seemingly equal.

The "Open" mixer configuration of the fluted mixing element also creates a layer of the material which rotates above the shearing gap and second undercut. This layer is formed because of the absence of the wiping flight. An almost independent, slow moving flow field appears to form in this region. The mass flow rate of this layer is equal to the mass flow rate over the second undercut which is about 50% of the mass flow rate entering the mixer. The layer is characterized by the long residence time and increases the residence time distribution of the mixer. RGB spectral analysis was used to calculate the time needed for the purging of the colorant out of the extruder. Purging time of the extruder equipped with the "Open" mixer is twice as long as that for the "Closed" fluted mixer. Recorded video of the experiment, on a glass window extruder showed the development of the slow moving layer in the "Open" mixer. The longer residence time of the layer with the "Open" mixer is also calculated by 3D FEM simulation. The long residence time of this layer can explain some extrusion problems such as polymer melt degradation. Thus, even if the "Open" fluted

mixer is easier to manufacture, it is not recommended for processing thermally sensitive polymers.

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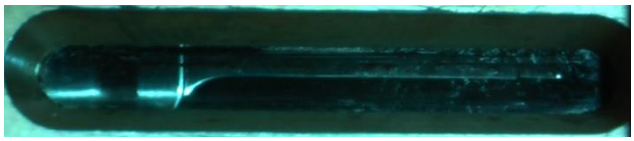
20. http://www.imatek.co.uk/product-r6000.php
21. http://www.compuplastvel.com

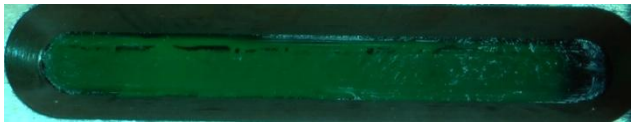
APPENDIX 1

RESIDENCE TIME VIDEO SAMPLES
"Open" mixer

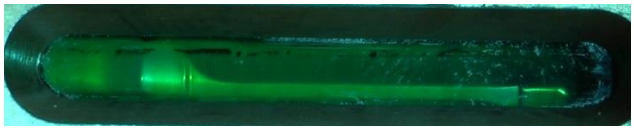
T = 0 min



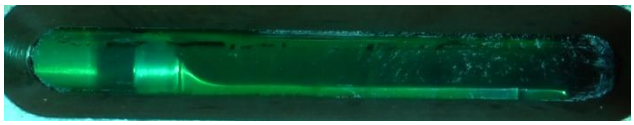
T = 10min



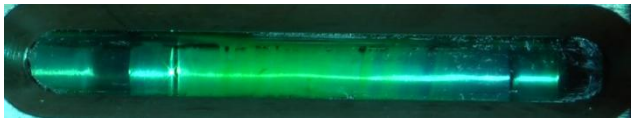
T = 20 min



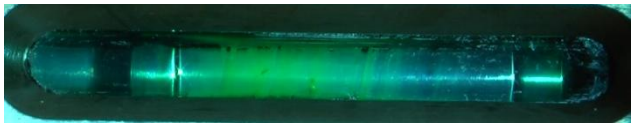
T = 30 min



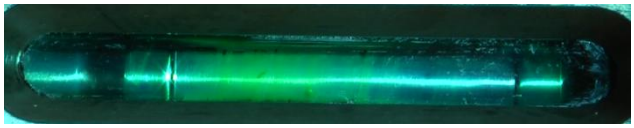
T = 40 min



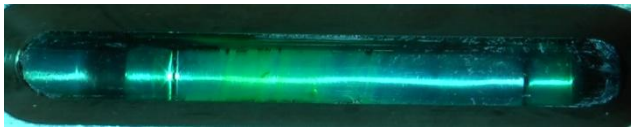
T = 50 min



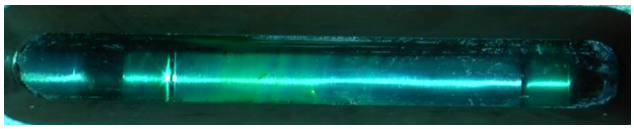
T = 60 min



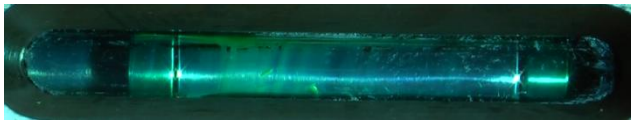
T = 70 min



T = 80 min

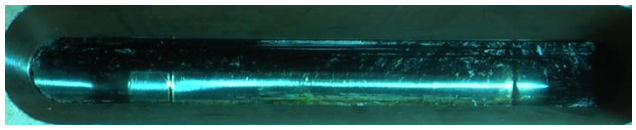


T = 90 min

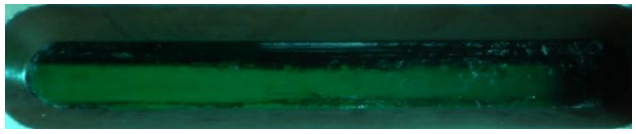


RESIDENCE TIME VIDEO SAMPLES
"Closed" mixer

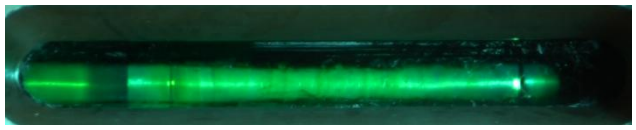
T = 0 min



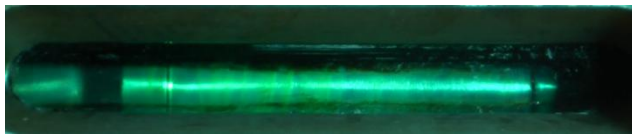
T = 10 min



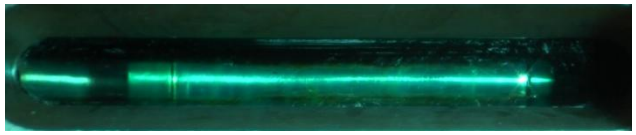
T = 20 min



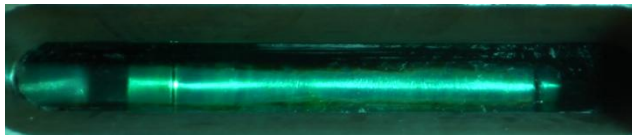
T = 30 min



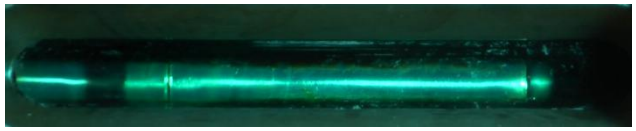
T = 40 min



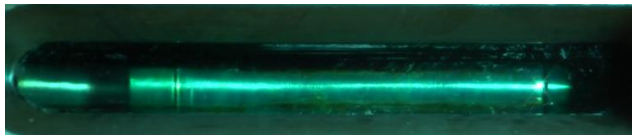
T = 50 min



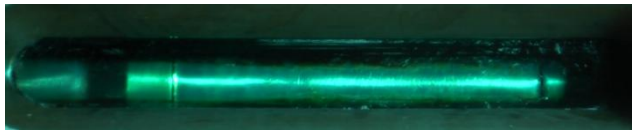
T = 60 min



T = 70 min



T = 80 min



T = 90 min