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PRODUCT-RELATED PROCESS DATA ACQUISITION IN BLOWN FILM EXTRUSION

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Abstract

In today's advanced plastics processing industry, a quality-based control of an entire production line is desirable. This requires a product-related process data acquisition allowing to merge process data and quality data with high accuracy. In this context, an approach for the blown film extrusion process will be presented. An experimental study confirms that the tool of residence time distribution analysis is suitable to identify the system behavior of a blown film line. On that basis, suggestions are made on how to proceed with the implementation of a product-related process data acquisition.

Introduction

Blown film extrusion is an important manufacturing process for the continuous production of thin plastic films, e. g. for packaging applications. Over the last decades, efforts in research and development have resulted in sophisticated machines and equipment allowing output rates exceeding 1000 kg/h. It is evident that a high line speed and maximum output rates are key requirements for a competitive mass production of plastic films.

Nevertheless, product quality is of overriding importance. There is already a large number of publications dealing with the development of blown film properties, their fundamental correlations with process parameters and the possibility of their prediction (e. g. [1-3]). But the gap between the scientific approaches on the one hand and the transfer into practical applications on the other hand has not been bridged yet. Thus, the holistic integration of a reliable system enabling an automated product quality-based process control of film blowing is still part of a vision. In the course of the progressing digitalization of the plastics processing industry, it is, therefore, promising to push forward research efforts in this area. An important starting point is the implementation of a product-related process data acquisition which needs to ensure that process data and quality data are merged consistently and as accurate as possible in relation to a finite produced unit.

With regard to blown film extrusion, the following conceptual question arises: What is the individual "processing history" of a specific piece of film taken from the final wrap at a certain position? In other words: How do we trace a single granule on its way through the entire process and use process data to describe its transformation from bulk material via viscous melt into a solid film?

The aim of this paper is to introduce an approach for the implementation of a product-related process data acquisition in blown film extrusion using residence time distribution analysis as a tool. Some basic considerations and methods are explained briefly. For demonstration purposes, it presents first results of an experimental study.

Product-related Process Data Acquisition

The general idea of a product-oriented perspective in process data acquisition (PDA) is neither new nor limited to the plastics processing industry. But it is still relevant today. For example, a concept for an advanced information system for machine operators in the pulp industry has already been presented in [4] in 1995. A more recent publication from 2016, for instance, discusses the issue of traceability regarding continuous processing in the pharmaceutical industry [5].

PDA in continuous processes, such as blown film extrusion, is usually time-based. That is, various sensor signals measured at any location in the blown film line are stored with an absolute time stamp and most probably on a common time base. In this context, there are three key issues regarding the implementation of a product-related PDA. First: Sensor signals detected at fixed locations in a continuous process are generally representative for the entire material stream [5]. On that basis, the absolute time stamp of a recorded sensor signal can be shifted towards the end of the extrusion line, where the product exits the system. This time shift depends on the sensor position in the process and the underlying operating point, e. g. regarding line speed. Second: The moment the final product exits the process, e. g. film being winded, the time reference becomes useless. It has to be replaced by a more suitable one, which is length for continuously manufactured products. Consequently, a time-to-length transformation is essential. Third: Since it is not practicable to track one single granule an appropriate reference quantity has to be chosen. In an extrusion process, it is reasonable to describe the "processing history" of a defined reference volume. Assuming a constant density, it moves through the system at a constant volume flow rate. Hence, its nominal average residence time in the system or even in each process section, such as the extruder, the die or the film bubble, can be determined. This allows the allocation of sensor signals in terms of a time period.

Against this backdrop, the knowledge of the residence time distribution (RTD) of the process is a necessary prerequisite for the implementation of a product-related PDA. In blown film extrusion, the RTD of the entire line is very much dependent on the technical equipment used and further influenced by the processing conditions. Therefore, experimental measurements of the RTD are useful to determine these dependencies and can serve as a basis for a modeling approach. There are not many reports on such investigations yet, with exception of [6]. In this study, inline UV-VIS spectroscopy and optical imaging were used to determine the RTD of a lab-scale blown film line under varying processing conditions.

Residence Time Distribution

The concept of RTD has already been introduced in the 1950s [7]. At this point, only a brief summary of some fundamentals is given, following [8].

Let $c_{in}(t)$ be the concentration of a tracer material that enters a system at the time t_0 in form of a step input:

$$c_{in}(t) = \begin{cases} 0 & for\ t < t_0 \\ c_{in} & for\ t \geq t_0 \end{cases} \tag{1}$$

Then the cumulative RTD function F(t) is determined directly from the measured concentration $c_{out}(t)$ of the tracer material leaving the system:

$$F(t) = \frac{c_{out}(t)}{c_{in}} \quad for\ t \geq 0 \tag{2}$$

The RTD function E(t) is the derivative of F(t) with respect to time and its first momentum equals the mean residence time t_m of the system:

$$t_m = \int_0^\infty t \cdot E(t)dt \tag{3}$$

In a system with a volume V and a constant volume flow rate Q the mean residence time is identical to the nominal average residence time $\bar{t}$:

$$\bar{t} = \frac{V}{Q} \tag{4}$$

There is a variety of models used to describe the RTD of ideal and real systems. An overview in the field of polymer extrusion is exemplarily given in [9]. In the context of this study, the approach presented in [10] is used to approximate the measured data for a blown film line. The model aims to describe real systems by means of two parameters, η and ε. A value for η deviating from unity indicates imperfect mixing in the system, whereas positive values for ε express a delay in the response of the system. The cumulative RTD function, taken from [10], is:

$$F(t) = \begin{cases} 0 & for\ 0 < t \leq \epsilon \\ 1 - \exp\left[-\eta\left(\frac{t-\epsilon}{\bar{t}}\right)\right] & for\ t \geq \epsilon \end{cases} \tag{5}$$

Experimental Study

The RTD of a small-scale blown film line was determined for three different operating points. Color changes from natural to blue and vice versa were performed and measured with an inline spectrophotometer to identify the system behavior.

Materials

The polymer used in this study was a low-density polyethylene named LDPE LD 151 BW, manufactured by ExxonMobil. It had a solid density of 0.934 g/cm³ and a melt flow rate of 3.0 g/10min at 190 °C and 2.16 kg. For the color change a blue masterbatch, manufactured by A. Schulman, was added with a concentration of 3 wt%.

Equipment

Figure 1 gives an overview of the blown film line and the installed sensors. The "hot part" part of the blown film line consisted of a grooved-barrel extruder and a spiral mandrel die, which were connected by a pipe. The mass flow rate and the film thickness are controlled automatically by the screw speed and the haul-off speed, respectively.

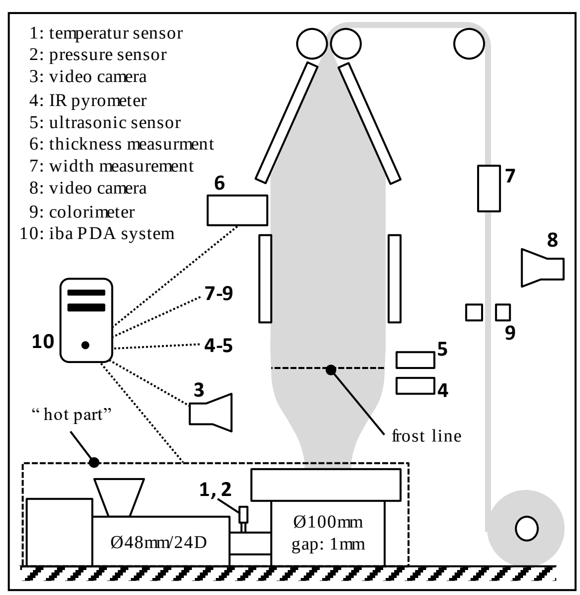

Figure 1. Schematic overview of the technical equipment.

The color in the middle of the film web was measured with a transmission sensor ACS3 connected to the color measuring system colorCONTROL ACS7000, both manufactured by Micro-Epsilon. Two video cameras allowed the observation of the bubble formation zone and the film web. They have been used for time measurements, e. g. to determine the time delay between the die exit and the color sensor.

All process parameters from the plant control and sensor signals, including the camera recordings, were collected and stored on a common time base of 5 ms by means of a PDA system, provided by the iba AG. The actual time base of a single signal could deviate due to sensor and interface preferences.

Procedure

Starting from a steady operating state with natural material (I), a complete color change to blue material was performed as a step input to the extruder. At the same time, a virtual signal in the PDA system, representing the color of the present input, was switched manually. After a defined waiting period the change process was assumed to be completed so that a steady state was reached again. Next, a color change back to the natural material followed. This routine was applied for two additional operating points (II, III). Again, a waiting period after the transition from one operating point to the other ensured a steady state at the beginning of every color change. The waiting period was chosen according to experience from previous experiments and could be confirmed as satisfactory by observing relevant process parameters.

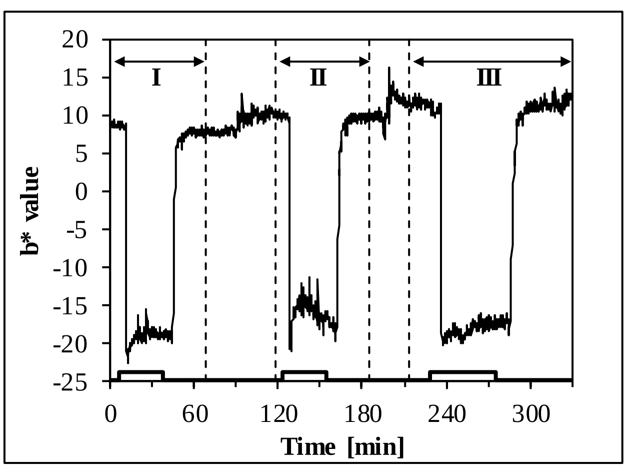

Figure 2. Measured b* value during the color change routine for three operating points (I, II, III). The bottom signal indicates the step input of the blue material.

Figure 2 shows the routine using the example of the measured b* value. It represents the intensity of the color blue (b* < 0) in the CIELAB color space. It was assumed that the b* value provided sufficient information about the color change because of the blue-colored masterbatch used as a tracer.

Table 1 provides detailed information about the process settings, where II is considered as the central operating point. In comparison, the film thickness and the mass flow rate were reduced by 1/3 in I and III, respectively. All other independent parameters were kept as constant as possible.

Table 1. Process settings of the operating points I, II and III with averaged measurement values in parentheses.

Parameter	**I**	**II**	**III**
mass flow rate, $\dot{m}$ [kg/h]	30	30	20
volume flow rate, Q [cm³/s]	8.922	8.922	5.948
film thickness, h [µm]	60	90	90
haul-off speed, v [m/min]	11.35 (11.35)	7.57 (7.62)	5.05 (5.51)
film width, b [mm]	393 (392)	393 (394)	393 (391)
frost line height, FLH [cm]	55.5	55.5	50.5

Results

Figure 2 illustrates that it is generally possible to use the b* value to describe the RTD of blown film line. In the following, only the rising parts of the measurement curves for each operating point are analyzed. They represent the color change from blue to natural, which is detectable with higher accuracy in practice. Thus, the falling edge in the bottom signal indicates the step input (t_0) of the natural material.

For the analysis, the b* value was interpreted as the concentration. As it deviated from zero for both, the natural and blue film, the curves needed to be shifted on the vertical axis. On top of that, the b* value depends on the film thickness, which is visible in the transition period from I to II (Figure 2). Moreover, there was strong noise in the data, so that an averaged b* value was used for the concentration c_{in} for both colors. It was calculated for a period of five minutes in steady state, just before the step input and at the end of the color change. During I and II the noise was partly caused by suddenly occurring bubble instabilities. They resulted in a wrinkled film web and hence affected the measurement. Next, the cumulative RTD could be determined with (2). For this analysis, the time delay ε in (5) equals the point, where F(t) exceeded the standard deviation (of the above mentioned steady state) times three for the first time. The curve fitting toolbox implemented in MATLAB was used to calculate the remaining parameters η and $\bar{t}$ in (5). Table 2 summarizes the results of the curve fitting.

Table 2. Results of the curve fitting using (5) as the model function. The parameter ε is fixed.

Parameter	I	II	III
η	5.877	6.721	6.418
$\bar{t}$	512	561	864
ε	341	374	576
$\varepsilon/\bar{t}$	0.666	0.666	0.666
R^2	0.9724	0.8907	0.8136

Figure 3 depicts the approximation using operating point III as an example and Figure 4 shows the corresponding film bubble at defined times. It is evident, that the model describes the RTD function of the blown film line appropriately until $\bar{t}$. Then, the model tends to overestimate the measured values in this specific case. Consequently, the definition of a reliable end time for the color change is challenging. Even at the time $t_{99.9\%}$ when F(t) equals 99.9 %, which could suggest that the remaining color fraction should not be significant, it is still visible in the video footage (Figure 4).

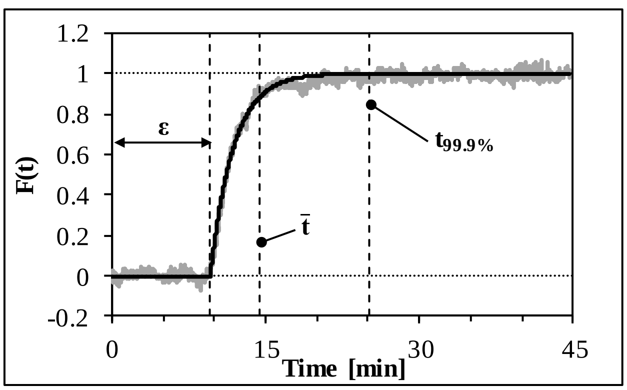

Figure 3. Measured (grey) and fitted (black) cumulative RTD function F(t) of operating point III.

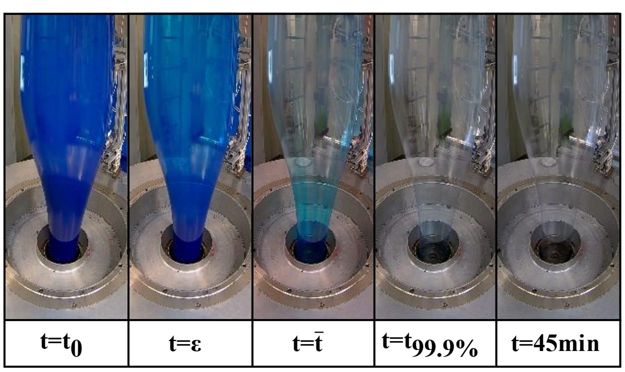

Figure 4. Snapshots for operating point III recorded with the iba system. A time shift of 81 s has been applied to synchronize the video footage with the colorimeter.

In blown film extrusion, the delay ε has two components: one results from the complex flow through the "hot part" of the machine (ε_1) and the other corresponds to the translational movement of the film bubble and film web (ε_2). The second part is predictable to a great extent because the haul-off speed and the distance from the frost line to the colorimeter is known. Moreover, an estimation of the period t_p for a film element to move from the die gap to the frost line is feasible, for instance using (6), where v_0 is the melt delivery rate [11].

$$t_p = \frac{FLH}{v - v_0} \cdot ln\left(\frac{v}{v_0}\right) \tag{6}$$

A comparison of the fitted RTD functions is shown in Figure 4. It confirms the dependency of the RTD on the underlying operating conditions (Table 1) as expected. The reduction of the film thickness by 1/3 ($h_I = 2/3 \cdot h_{II}$) causes a reciprocal increase of the haul-off speed ($v_I = 3/2 \cdot v_{II}$). As a consequence, the delay decreases (II vs. I). Additional time measurements have confirmed a decrease by approx. 1/3 of ε_2. In contrast, the decrease of the mass flow rate by 1/3 ($\dot{m}_{III} = 2/3 \cdot \dot{m}_{II}$) affects the entire system (II vs. III). In this case, both components of ε should change reciprocally ($\varepsilon_{III} \approx 3/2 \cdot \varepsilon_{II}$). Again, additional time measurements could confirm this tendency. It should be highlighted that the influence of the mass flow rate on the RTD of the blown film line is clearly superior. This finding has already been stated in [6].

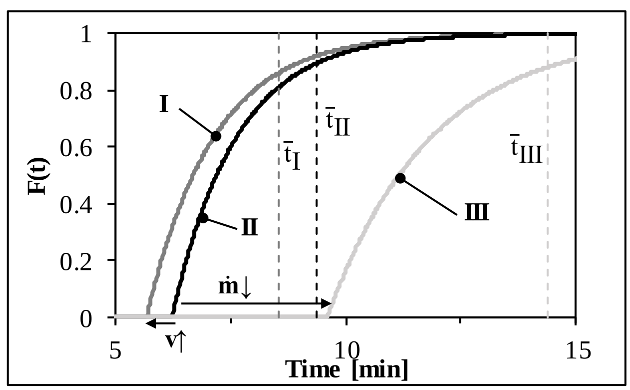

Figure 5. Comparison of the fitted F(t) of all three operating points (I, II, III). The time axis is zoomed in.

Regarding the model parameters (Table 2), it is striking that the ratio $\varepsilon/\bar{t}$ is identical for all three operating points. This might indicate that the parameter variations in this study, indeed, cause a consistent change in the RTD of the blown film line. The significance of the parameter η in this context has not yet been fully investigated. But as it is believed to describe the mixing efficiency of the system the occurring deviations are surprising in the first place. Especially the discrepancy between the values for operating point I and II does not meet the expectations.

Implementation of a Product-related PDA

In the following, some suggestions on how to proceed with the implementation of a product-related PDA are presented. Operating point III serves as a demonstration scenario. As an example, the temperatures of the melt and the film at the frost line are used as parameters within the "hot part" and the bubble area, respectively. With respect to the product quality, the film width serves as an inline quality parameter. For the sake of simplicity, the winder is assumed to be located directly behind the colorimeter.

At first, the time shifts along the bubble and film web can be determined. Following a mark on the bubble, the pyrometer-specific time shift of 70 s was measured. The time t_p results from (6) and equals 11 s. As the IR pyrometer was located at the frost line (Figure 1), the period of 81 s in total represents the delay time ε_2. It has already been used to synchronize the video footage with the colorimeter (Figure 4). The distance between the width measurement device and the colorimeter was 1.8 m. Using the actual haul-off speed (Table 1) the time shift for the width signal is approx. 20 s. As a next step, the time-to-length transformation mentioned at the beginning has to be applied. For this, the web speed (at the winder) serves as the transformation factor. Theoretically, the time base of 5 ms would result in a length base of approx. 0.4 mm, using the target value for the haul-off speed. In practice, such a small length base is probably pointless. Assuming a line speed of 50 m/min and a time base of 1 s, which might be a more realistic scenario in practice, the length base would already increase to 0.8 m.

The treatment of the remaining components of the process is much more challenging. Even a more detailed consideration of the stretching in the bubble formation zone might be of interest. Moreover, the determination of the time t_p possibly requires higher accuracy than that achieved by using (6). Regarding the "hot part", detailed information about the individual components, namely the extruder, the pipe and the die, is generally beneficial. The obtained RTD model in this study needs further investigation. At this stage, a complete implementation of a product-related PDA is not yet achieved. For example, the measured melt temperature has to be related to reference volume (V*). The RTD curve can be used to estimate a suitable quantity by means of characteristic times, like $\bar{t}$ and $t_{99.9\%}$. The latter could be used as a maximum residence time. However, it is necessary to eliminate the influence of the bubble and the web on the RTD curve. It might be expedient to use the isolated nominal average residence time of the "hot part" ($\bar{t}_1$) for the time shift of the melt temperature signal. It could be calculated by subtracting ε_2 from $\bar{t}$. Furthermore, the signal has to be averaged over a particular time period that is relatable to the reference volume. In sum, further investigation is needed to develop a complete model.

Conclusions

The analysis and modeling of the RTD of a blown film line is a suitable tool to identify the system behavior and its dependency on the processing conditions. On that basis, it is generally possible to implement a product-related PDA, so that the "processing history" of a piece of film can be tracked with higher accuracy.

A key requirement is the time shift of sensor signals according to their measurement position in the process. This is practicable for the film bubble and film web area. In a steady state process, the line speed and, consequently, the time shift is constant. It is determined directly by the process settings. Sensor signals detected within the "hot part" of the machine should be related to the volumetric flow rate. As the RTD shows a time delay and mixing effects, the definition of a reference volume, depending on the operating point, is necessary. Thus, sensor signals recorded over a specific time period are relatable to a particular reference unit. The more information on a single machine component in terms of RTD is available, the more accurate the tracking of a reference unit can be. As a consequence, further investigation with detailed analysis of the RTD of the extruder, the pipe and the extrusion die is needed. Of course, an expansion of the system, taking the hopper and the material supply system into consideration, is conceivable.

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