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An Experimental Study on Process-oriented Scale-up / Scale-down in Blown Film Extrusion

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Abstract. The transfer of experimental test results from a small-scale system to a large-scale production system is known as scale-up or, conversely, scale-down. For film-producing companies, scale-up is a common procedure in the development process of new composite films or material recipes, where the main objective is to obtain equal film properties in the laboratory and the production environment. The process-oriented scale-up / scale-down strategy has been developed as a systematic and practicable approach for the blown film extrusion process. For the recent study, a scale-down scenario with a scaling factor k=1/8 is investigated and the results are compared with a previous study (k=1/10). Measured mechanical properties of produced film samples serve as a basis to confirm the feasibility of the approach and the reproducibility of the experimental results. The corresponding industrial production process (> 800 kg/h) determines the underlying process conditions.

INTRODUCTION

Blown film extrusion is an important manufacturing process for single- and multi-layered films. The polymer melt is extruded through an annular die, resulting in a tube which is inflated with air so that it expands into a bubble. Next, the bubble is collapsed, taken up by nip rolls and finally winded up. After leaving the die, the bubble is typically cooled with air provided by a cooling ring until the material solidifies at the frost line. Additional internal bubble cooling (IBC) is used in state-of-the-art production plants. At the same time, the bubble is stretched in the machine direction (MD), as it is taken up with a defined speed, and in the circumferential direction (CD), due to the inflation. Accordingly, the area from the die exit to the frost line is called bubble formation zone. Final film properties are predominantly defined within this zone resulting from the interaction of thermo-rheological processes, such as cooling, biaxial stretching leading to molecular orientation, relaxation and crystallization.

During the development process of new composite films or material recipes manufacturers are commonly confronted with scale-up. Generally, it is known as the transfer of operating conditions and testing results from a laboratory-scale system to a large-scale production system. In blown film extrusion, this transfer is challenging because of the aforementioned correlation between final film properties, which are of major interest, and the underlying process parameters that, in turn, strongly interact with each other. Furthermore, the technical equipment of a production environment differs from that in a laboratory so that the process is affected or even limited due to plant-specific restrictions. Taking these circumstances into account, the process-oriented scale-up / scale-down strategy (POSS) has been developed as a systematic and practicable approach.

This paper presents the results of an experimental validation of the POSS. Moreover, a comparison with a previous study [1, 2] is drawn. At first, the theoretical basis of the POSS is described briefly following [2] and [3].

THEORETICAL BASIS OF THE POSS

The basic assumption of scale-up / scale-down in blown film extrusion is that films produced on differently scaled plants show similar properties provided that all relevant influencing variables and thermo-rheological

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processes within the bubble formation zone are similar. In this context, two fundamental requirements for a process-oriented scale-up / scale-down are defined:

- 'Geometrical similarity': is achieved by keeping biaxial stretching ratios equal, that is the draw-down ratio (DDR) for MD and the blow-up ratio (BUR) for CD.
- 'Dynamic similarity': is achieved by keeping processing conditions similar in terms of process time, which is the period for one small element of the film to pass through the bubble formation zone.

Provided that the material composition, the layer structure as well as the melt temperature at the die exit (T_0) are comparable, similar material characteristics, such as density, viscosity or relaxation time, and similar material behavior during bubble formation can be expected. Since the final film thickness is an important product characteristic and, moreover, affects other film properties, it has to be the same for both scales. Consequently, this requirement also applies to the die gap width.

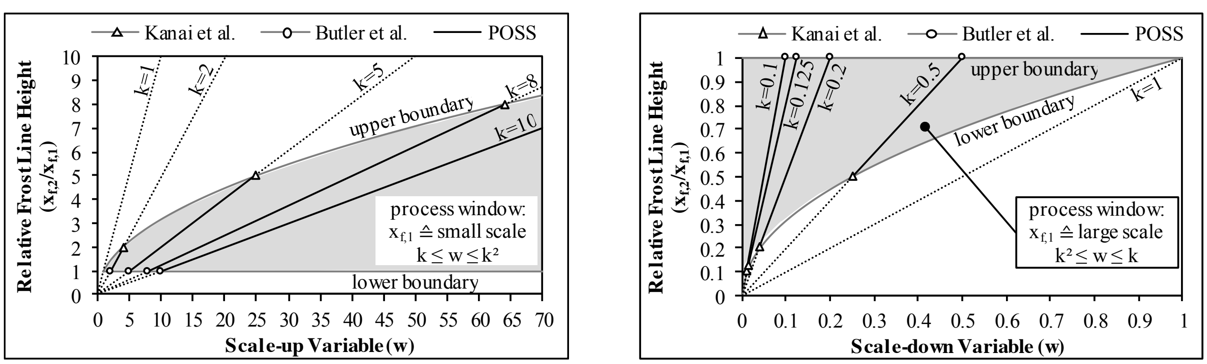
Finally, an operating point can be transferred between two blown film lines under process-oriented scale-up / scale-down conditions by adjusting the mass flow rate ($\dot{m}$) within a process window as a function of the frost line height (x_f) and a constant process time (t_p). In practice, the mass flow rate is scalable with the scale-up / scale-down variable w (Eq. 1) and the corresponding frost line height is calculated according to Eq. 2. The subscripts 1 and 2 refer to the initial process state in a scale-up / scale-down scenario and the target operating point, respectively. The scaling factor k equals the ratio between the die diameters (d_0) (Eq. 3, [4]) and C is a constant depending on the initial process. [2, 3]

$$\dot{m}_2 = w \cdot \dot{m}_1 \tag{1}$$

$$x_{f,2} = \frac{w}{k} \cdot t_{p,1} \cdot C_1 \tag{2}$$

$$k = \frac{d_{0,2}}{d_{0,1}} \tag{3}$$

As a result, the POSS allows to set the target process parameters in accordance with processing and plant-specific restrictions, for example, the maximum mass flow rate or the cooling capacity. Due to this flexibility the strategy is more feasible compared to existing models introduced in the past by Kanai et al. [5] and Butler et al. [6]. Instead of a process window their approaches calculate just one single, fully determined operating point which is not necessarily practicable under the given restrictions of the specific scale-up / scale-down scenario, especially for large differences in scale [2, 3]. Figure 1 shows the process window of the POSS and the relation to the other strategies which are interpreted as boundaries.



(a) (b)

FIGURE 1. Visualization of the process window according to the POSS in case of scale-up (a) and scale-down (b).

EXPERIMENTAL PROCEDURE

To confirm the practicability of the POSS an experimental study is carried out. A production process of a three-layer polyethylene film on an industrial blown film line (d_0 > 600 mm) is used as a reference process (Run 0) and scaled down to a small-scale plant (k=1/8). Six operating points with different mass flow rates are calculated according to the scale-down conditions and performed experimentally (Run 1-6). The mass flow rate of the production process exceeded 800 kg/h. A single-lip cooling ring and an IBC is used for bubble cooling in the industrial scale, whereas the latter is missing in the laboratory-scale plant. Table 1 presents the process parameters of the scale-down scenario. More detailed information on the reference process is available in [2].

TABLE 1. Process parameters for the reference process (Run 0) and the laboratory-scale operating points (Run 1-6).

Operating Point	w -	DSO (kg/hmm)	BUR -	DDR -	T_0 (°C)	x_f (m)	t_p (s)
Run 0	1	1.19		20.4		0.930	
Run 1	0.019	0.18		18.6		0.188	
Run 2	0.023	0.22		18.6		0.228	
Run 3	0.027	0.26	1.66	18.5	195	0.254	5.1
Run 4	0.032	0.30		18.5		0.315	
Run 5	0.036	0.34		18.5		0.337	
Run 6	0.040	0.38		18.6		0.368	

The mass flow rate is expressed as the die specific output rate (DSO). That is the mass flow rate related to the die diameter. Deviations occur regarding the DDRs but, however, they are acceptable because films with the same target thickness are produced. Moreover, the layer structure and the material composition used are identical for both scales. The process time has been determined for Run 0 by means of a measured velocity profile and the experimental bubble contour [2]. In practice, the frost line height is set to the target value by adjusting the amount of cooling air. The values for x_f in Table 1 are determined with the help of pictures taken from the bubble. Due to a non-symmetric bubble shape, which appeared in some instances, the control of the frost line height is difficult, leading to variations regarding the results (Fig. 2).

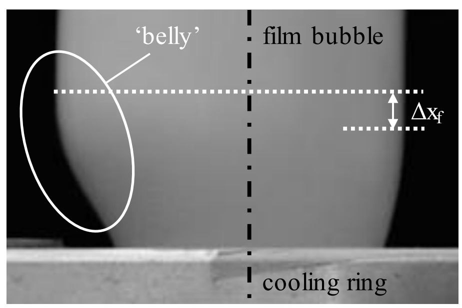


FIGURE 2. Non-symmetric bubble shape leading to variations of x_f in experimental Run 2 as an example.

EXPERIMENTAL RESULTS

Film samples are taken from every run, including the reference, and their mechanical properties are measured according to DIN EN ISO 527-3 (tensile properties, Fig. 3) and DIN EN 14477 (puncture resistance, Fig. 4). Each run is characterized by the mean value of ten samples. Moreover, the dotted lines in Figure 3 indicate the average of the laboratory-scale runs (Run 1-6) so that the comparison with Run 0 is more intuitive.

Figure 3 shows that both, the tensile stress at yield (Fig. 3a) and the modulus of elasticity (Fig. 3b), are reproducible in the laboratory-scale (Run 1-6) under process-oriented scale-down conditions. The accuracy is considerably lower in CD which might be explained by the non-symmetric bubble shape leading to local variations in molecular orientation and film thickness. For all properties, an offset between the average of Run 1-6 and Run 0 is observable. Since its tendency is consistent within Figure 3a and Figure 3b, respectively, a systematic difference regarding the processing conditions in the laboratory and the production environment is conceivable. Possible reasons can be many, but may arise from deviations regarding the technical equipment (extruder sizes, screw and die design, cooling system, IBC). It has to be stated that the offset of the modulus of elasticity in MD is remarkably higher in contrast to CD (Fig. 3b).

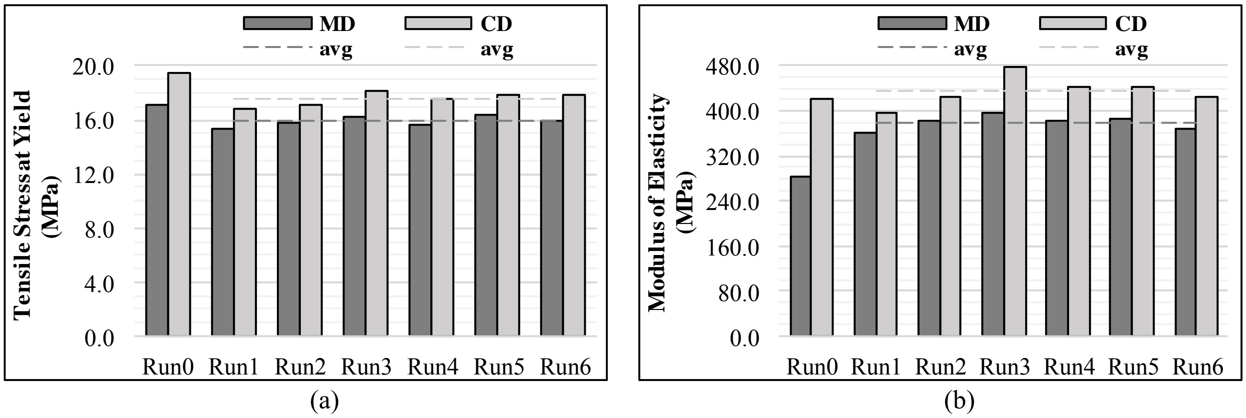


FIGURE 3. Tensile stress at yield (a) and modulus of elasticity (b) for Run 0-6 in machine and circumferential direction.

The puncture resistance test is performed in normal direction of the film. Figure 4 shows the measured values for the maximum force (named puncture resistance), the elongation and the penetration energy. Puncture resistance relates to the ratio of anisotropy regarding the biaxial molecular orientation and, hence, the film's strength. It is assumed that an increasing ratio of anisotropy leads to decreasing puncture resistance. Again, the laboratory runs confirm a good reproducibility of the properties but the aforementioned offset with respect to the production process is still detectable. The measured maximum force in Run 2 is noticeably lower which correlates with the lower mean thickness of its film samples. However, thickness deviations do not explain the higher reference value (Run 0).

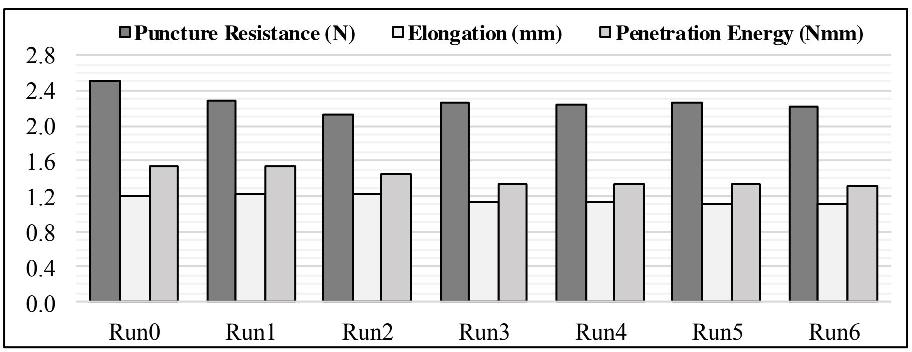


FIGURE 4. Puncture resistance, elongation and penetration energy for Run 0-6.

As mentioned above, the presented results are comparable to those of a previous study [1, 2], where the same production process has been scaled-down to an even smaller laboratory machine (k=1/10) applying the POSS. The average values of the laboratory runs (Run 1-6) from both studies and the results from Run 0 are shown in Figure 5. Regarding the tensile stress at yield (Fig. 5a) a very good accordance is observable among the small-scale processes in MD and CD. This gives rise to the assumption that, besides geometrical and dynamic similarity, the transferability of operating conditions is the more reliable the more comparable the technical equipment of the reference and the target blown film line is. In fact, this is the major challenge during up-scaling in practice. Nevertheless, the results still confirm that film properties are reproducible under process-oriented conditions with a sufficient accuracy since all produced film samples meet the specific technical requirements of the examined product. The measured values for the modulus of elasticity (Fig. 5b) do not allow to draw any clear conclusions. In CD both target processes (k=1/8 and k=1/10) have a positive offset compared to the reference, whereas in MD the offset is lower but in opposite directions. Here, it has to be noted that only mean values are compared in order to reduce the complexity but the ranges of the samples still overlap for several operating points. The results of the puncture resistance test (Fig. 5c) seem to reveal a downward tendency regarding the maximum force and the penetration energy with increasing difference in scale, while the corresponding elongation of the film varies very little. Once again, the given data do not allow to determine a definite process parameter that could be correlated with the observations. It is assumable that the influencing factor is not exclusively detectable within the bubble formation zone and therefore is disregarded in the POSS. This, for example, applies to the corona pretreatment and IR-heaters which are installed at the referenced production line. Indeed, a decreasing influence on the puncture resistance properties for the investigated film is described in [3].

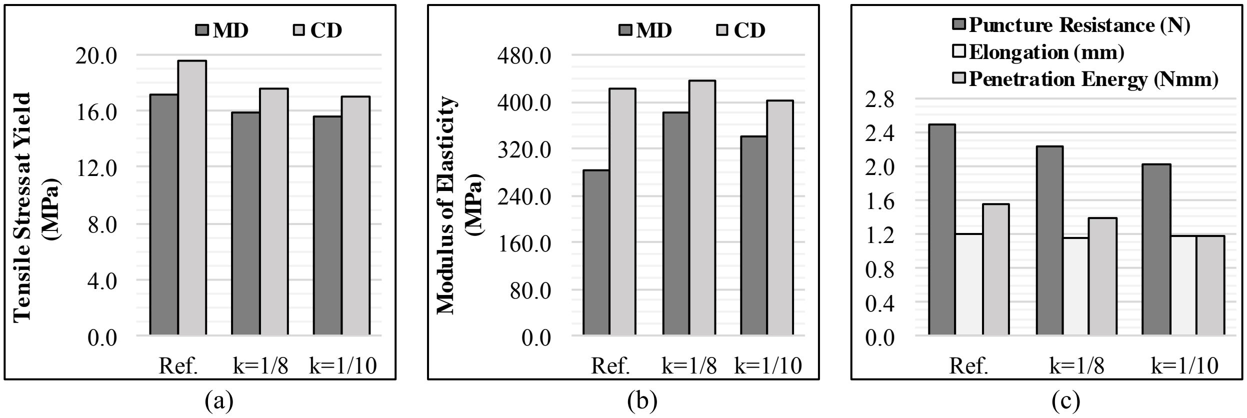


FIGURE 5. Mechanical properties from tensile test in MD and CD (a, b) and puncture resistance test (c) for two scale-down scenarios (k=1/8, k=1/10) in comparison with Run 0 as the common reference process (Ref.).

CONCLUSION

All in all, the referenced industrial production process has been scaled down successfully to an eight times smaller laboratory plant (k=1/8) which confirms the general feasibility of the POSS. The measurement results of the considered mechanical properties are in good accordance. A very good reproducibility is achieved for the laboratory runs which indicates that it is valid to scale the operating conditions within the process window of the POSS, taking the relation between the mass flow rate and the frost line height and, hence, the corresponding process time into account. Nevertheless, an offset between the laboratory runs and the industrial process is observable. To a certain degree this is caused by the limitations of the approach: any influences outside the bubble formation zone are neglected or assumed to be constant; deviations regarding the technical equipment, such as the extruder design or the installed cooling system, are not explicitly considered.

However, the POSS offers the flexibility to scale the mass flow rate in accordance with plant-specific restriction instead of defining just one fully determined operating point. Therefore, the practicability is increased in contrast to existing approaches presented in the past. The comparison between the current experiments and a previous study shows that the process-oriented strategy has a larger application area. Eventually, the POSS helps to make the development process of new products more efficient because material, time and, thus, cost savings can be achieved.

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