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A New Scale-up / Scale-down Method for the Blown Film Extrusion

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Abstract. The development of innovative film products is a two-step process: New composite films or material recipes are first experimentally tested on a laboratory-scale blown film line, and then the results regarding process conditions and final film properties are transferred to a large-scale production plant. This procedure is generally known as scale-up. However, the transferability of results is not always ensured because of processing- and plant-specific restrictions. Thus, this paper presents a process-oriented scale-up / scale-down strategy (POSS), that should provide higher flexibility in practical use compared to existing scale-up strategies. To prove the feasibility of the process-oriented strategy, a series of experimental runs was carried out. An industrial production process on a high-capacity blown film line (> 750 kg/h) was selected as the starting point for a scale-down to a small-scale laboratory plant (scale-down factor of ten). Finally, mechanical properties of the film samples taken from the production process and the laboratory runs were measured and compared. The comparison showed that films with similar properties could be produced under process-oriented scale-down conditions.

Keywords: blown film extrusion, process-oriented scale-up / scale-down strategy, film properties, process time
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INTRODUCTION

The blown film process is characterized by simultaneous stretching of the molten polymer in machine direction (MD) and circumferential direction (CD), which generally leads to anisotropic mechanical properties of the solid film. A cooling ring provides an air stream to cool the bubble while an additional system for internal bubble cooling (IBC) is optionally installed on large-scale blown film lines. Primarily influenced by the cooling conditions, dynamic processes, such as crystallization and relaxation, take place in the bubble formation zone, too. The period for one small element of the film to move from the die exit to the frost line is defined as the process time (t_p).

For film-producing companies, it is important to offer innovative and high-quality products in order to stay competitive on international markets. The development of new composite films or material recipes is usually performed on a laboratory-scale blown film line, because this saves materials, time and, thus, costs. Subsequently, the process conditions tested on the small-scale plant and the resulting final film properties need to be transferred to a large-scale production plant. This transfer of results between two differently scaled blown film lines is called scale-up [1] or, conversely, scale-down. Obtaining equal film properties independent of the plant's scale is the main objective during scale-up / scale-down. It is well known that blown film properties correlate with the underlying process parameters that, in turn, strongly interact with each other. Furthermore, the technical equipment of a production plant differs from that in a laboratory; hence, the adjustability of certain process parameters might be limited due to plant-specific or processing restrictions. Taking all these relations into account, the demand for a systematic and practicable scale-up / scale-down strategy arises.

Therefore, this paper presents the theoretical background and an experimental validation of a process-oriented scale-up / scale-down strategy (POSS), which, on the one hand, is based on existing scale-up strategies. On the other hand, since a degree of freedom is introduced without neglecting the aforementioned interdependences of major process influences, the POSS ought to be more flexible in practice.

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PROCESS-ORIENTED SCALE-UP / SCALE-DOWN STRATEGY

In a scale-up / scale-down scenario, the difference in size between the laboratory plant (subscript: lab) and the production plant (subscript: pro) is generally described by the scaling factors k and s. They are defined as the ratios between the die diameters d_0 and the die gap widths h_0, respectively [2].

$$k=\frac{d_{0,pro}}{d_{0,lab}} \tag{1}$$

$$s=\frac{h_{0,pro}}{h_{0,lab}} \tag{2}$$

The basic requirement for maintaining mechanical film properties, independently of the plant's scale, is equal stretching in MD and CD, which is ensured by keeping the draw-down ratio (DDR) and the blow-up ratio (BUR) constant. The DDR equals the haul-off speed divided by the melt delivery rate, and the BUR is calculated as the quotient of the bubble diameter at the frost line and the die diameter. In accordance with Pearson [3], this requirement is called 'geometrical similarity'. Here, it has to be noted that Pearson, as well as Kanai et al. [4], also suggested to leave the ratio between the frost line height (x_f) and the die radius (r_0) unchanged. In contrast, this condition is not included in the POSS, because it is too restrictive with regard to possible restrictions in practical use. Since the film thickness (h_f) is an important product characteristic and, moreover, affects other film properties, it should be the same for both scales. Consequently, the scaling factor s equals one in the POSS. This corresponds to the scale-up condition presented by Butler et al. [5], whereas Kanai et al. allow the factor s to deviate from one.

Another essential requirement of the POSS is called 'dynamic similarity', which is achieved by keeping processing conditions similar in terms of process time. Thus, time- and temperature-dependent processes within the bubble formation zone, affecting final film properties, are considered. For a precise approximation of the process time, its determination should be based on the real shape of the bubble and the actual profile of the film velocity. Assuming that measured data for the bubble contour and the velocity profile as functions of height above the die exit are available, the process time is calculated according to Eq. (3). Accordingly, the bubble formation zone is divided into n small segments, and the residence time for each segment is calculated as the quotient of its length l_i and a local average film velocity $\bar{v}_i$ [6].

$$t_p=\sum_{i=1}^{n}\bar{v}_i^{-1}\cdot l_i \tag{3}$$

Butler et al. introduced the dimensionless fabrication time ratio (FTR) as a scale-up variable. It is the ratio between the polymer-specific relaxation time and the process time [5]. They suggested to estimate the process time on the basis of a linear film velocity profile. Since this simplification is not considered to be universally reasonable in practice, the approximation with real data for the bubble contour and the velocity profile is preferred in the context of the POSS.

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. Here, it has to be assumed that processing influences due to thermal and mechanical stresses in the extruder and the die are negligible or, at least, comparable for the considered plants.

Finally, an operating point can be transferred between two blown film lines adjusting the mass flow rate ($\dot{m}$) and the frost line according to the following process-oriented scale-up / scale-down conditions (presented for scale-up):

$$\dot{m}_{pro}=w\cdot\dot{m}_{lab} \tag{4}$$

$$x_{f,pro}=\frac{w}{k}\cdot t_{p,lab}\cdot C_{lab} \tag{5}$$

$$C_{lab}=\dot{m}\cdot\left(\frac{1}{d_f\cdot h_f\cdot\rho_f}-\frac{1}{d_0\cdot h_0\cdot\rho_0}\right)\cdot\left[\pi\cdot\ln\left(\frac{d_0\cdot h_0\cdot\rho_0}{d_f\cdot h_f\cdot\rho_f}\right)\right]^{-1} \tag{6}$$

The flexible scaling of the mass flow rate with the variable w (Eq. 4) represents the aforementioned degree of freedom, which is a key element of the POSS. This enables the determination of suitable operating points within a process window. Theoretical boundaries for the value range of w are suggested to be k as the lower limit and k^2 as the upper limit. These boundaries represent the scale-up conditions for $\dot{m}$ according to the strategies by Butler et al. (k) and Kanai et al. (k^2). Under the condition of an equal process time for both scales, x_f is a function of the variable w and the parameters k, t_p and C (Eq. 5). In practice, the frost line height needs to be regulated, adjusting bubble cooling parameters such as the volumetric flow rate of the cooling air and/or its temperature. The constant C depends on the process state that is used as the starting point in the scale-up / scale-down scenario (laboratory process in case of scale-up). In Eq. (6), the variables d, h and ρ represent the bubble diameter, its thickness and the density of the polymer. The subscripts 0 and f indicate that it is either the corresponding value at the die exit or at the frost line.

As a result, the POSS allows to set the target process parameters $\dot{m}$ and x_f in accordance with existing processing- and plant-specific restrictions, for example, the maximum mass flow rate or the cooling capacity. Therefore, performing a scale-up / scale-down becomes more feasible, even for high values of k, which occur when high-capacity production plants are considered. In contrast to the POSS, the aforementioned scale-up strategies developed by Kanai et al. and Butler et al. calculate just one single, fully determined operating point for a given scale-up / scale-down scenario. Consequently, they do not provide sufficient flexibility to respond to possible constraints due to the production line or the laboratory plant.

EXPERIMENTAL PROCEDURE

Applying the process-oriented scale-up / scale-down strategy, an experimental scale-down was performed. A production process of a three-layer polyethylene film on a high-capacity blown film line ($d_{0,pro}$ > 600 mm) was used as the reference process (run 0). The mass flow rate exceeded 750 kg/h. For cooling the tubular film, a single-lip cooling ring and an IBC were installed. The large-scale process was transferred to a laboratory-scale plant, which was equipped with a single-lip cooling ring only. Six operating points with different mass flow rates were calculated and experimentally carried out on the small-scale plant (Run 1-6). Table 1 presents the corresponding process parameters.

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

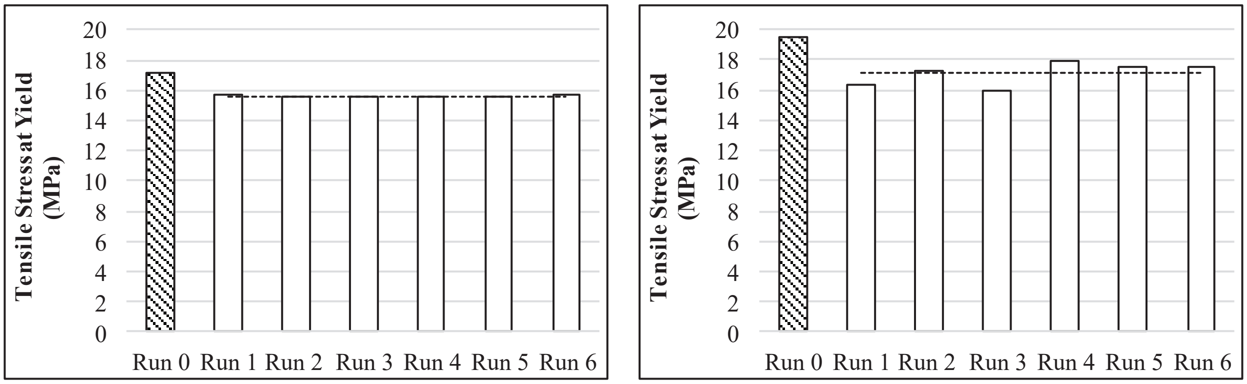
Operating Point	w -	DSO (kg/hmm)	BUR -	DDR -	T_0 (°C)	x_f (m)	t_p (s)
Run 0	1	1.1875	1.66	20.4	195	0.930	5.1
Run 1	0.011	0.125		16.7		0.110	
Run 2	0.013	0.150		16.7		0.135	
Run 3	0.016	0.188		16.6		0.167	
Run 4	0.019	0.225		17.3		0.186	
Run 5	0.022	0.263		17.5		0.238	
Run 6	0.026	0.313		16.9		0.276	

Furthermore, the scale-down factors k and s were ten and one, respectively. The film thickness, the layer structure and the materials used were identical for both scales. Regarding the DDRs, runs 1-6 seem to deviate systematically from run 0. Although the DDR should have been the same for all runs, achieving the target film thickness had higher priority during the experiments. Measured data for the velocity profile and the bubble contour of the reference process were used to determine the process time (5.1 s) according to Eq. 3. Applying the POSS, the same process time was expected for the laboratory-scale runs. This assumption was experimentally confirmed by means of Run 2. For this purpose, the bubble was marked with a viscous paint at the die exit and the position of the marked spot, passing the bubble formation zone, was recorded with a video camera. Thus, a measured process time of 5.4 seconds resulted, which is in very good accordance with the calculation. Finally, film samples were taken from every run, including the reference process, and their mechanical properties were measured according to DIN EN ISO 527-3 (tensile properties) and DIN EN 14477 (puncture resistance).

EXPERIMENTAL RESULTS

The following figures contain the measurement results of the tensile test (Fig. 1 and Fig. 2) and of the puncture resistance test (Fig. 3). Each run is characterized by the mean value of ten samples. Moreover, the dotted line indicates the average of the laboratory-scale runs (Run 1-6) so that the comparison with the reference process (Run 0) is more intuitive.

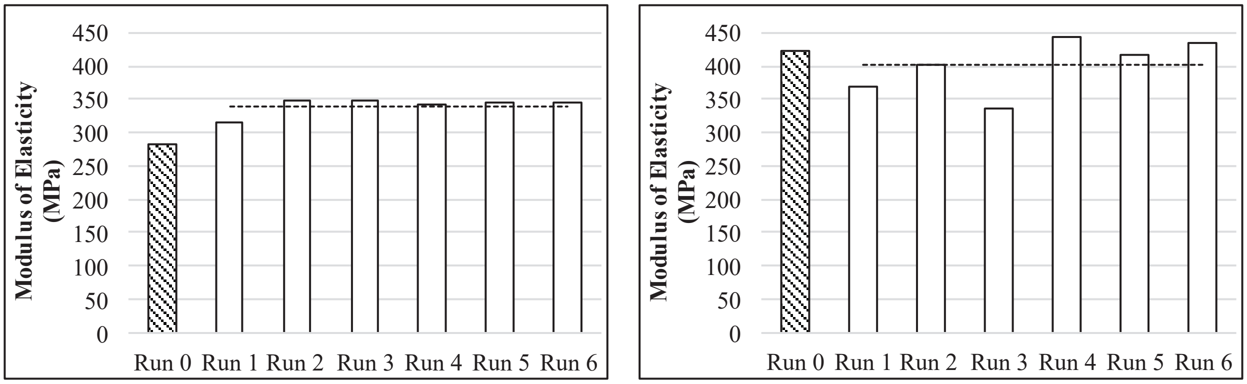
Figure 1 shows the tensile stress at yield in machine direction (Fig. 1a) and circumferential direction (Fig. 1b). The stresses in CD are somewhat higher than in MD or are nearly comparable. This does not meet the expectation, since the stretching in CD is considerably lower than in MD. It is possible that the BUR, however, is high enough to overcompensate for the molecular orientation induced by stretching in MD. The deviation of the average stress (Run 1-6) from Run 0 in MD (Fig. 1a) can be explained by the difference between the corresponding DDRs (Table 1). Nevertheless, the laboratory-scale runs demonstrate a very good reproducibility of the tensile stress at yield under process-oriented scale-up / scale-down conditions, and the results are similar to those of the reference process.



(a) (b)

FIGURE 1. Tensile stress at yield (a) in machine direction and (b) in circumferential direction for runs 0-6.

The modulus of elasticity was measured as a secant modulus between 0.75 % and 1.25 % of elongation. Figure 2 shows the test results in machine direction (Fig. 2a) and circumferential direction (Fig. 2b). For all runs, the modulus measurements in MD are lower than in CD, which is in accordance with the typical findings in the literature [7, 8]. The average of Run 1-6 in MD is nearly 20 % higher than that of Run 0, but the reproducibility of the POSS is still observed (Fig. 2a). Furthermore, there are noticeable variations in the results for runs 1-6 in CD (Fig. 2b). They might be caused by variations in the film thickness due to the absence of a thickness control system in the laboratory plant. It is possible that these irregularities lead to uneven film stretching and, hence, affect the modulus of elasticity.



(a) (b)

FIGURE 2. Modulus of elasticity (a) in machine direction and (b) in circumferential direction for runs 0-6.

Figure 3 shows the puncture resistance, the elongation and the penetration energy, resulting from the puncture resistance test. In general, the puncture resistance can be related to the ratio of anisotropy regarding the molecular orientation and, hence, the film's strength. It is assumed that an increasing ratio of anisotropy leads to decreasing puncture resistance. Considering the underlying BURs and DDRs (Table 1), the puncture resistance of Run 0 was expected to be higher than that of Run 1-6. The contrary finding (Fig. 3) could be explained by the different film thicknesses. It has to be noted that the mean thicknesses of the samples from Run 1-6 were slightly thinner than those from Run 0. The values for elongation and penetration energy are remarkably similar, for the laboratory-scale runs in particular.

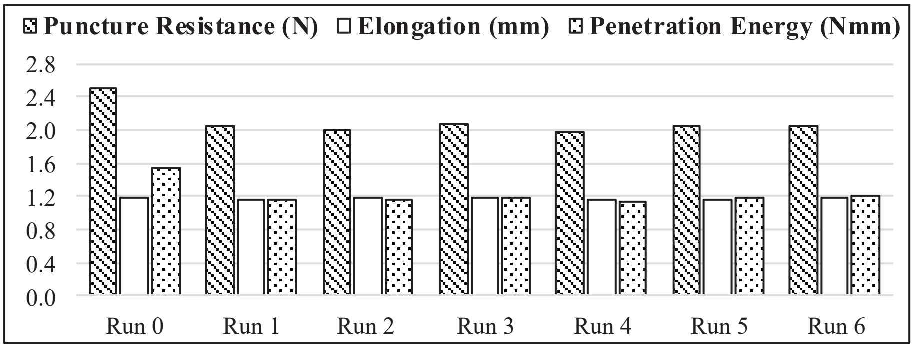


FIGURE 3. Puncture resistance, penetration energy and elongation for runs 0-6.

All in all, the results confirm a very good reproducibility of the considered mechanical properties, applying the POSS. Variations are generally wider in circumferential direction than in machine direction. Since the findings do not always correspond to the expected outcome, it has to be noted that the material composition used seems to be relatively robust. Therefore, the material characteristics might have a big impact on the final film properties and, thus, superimpose the processing influences to some extent.

CONCLUSION AND OUTLOOK

The process-oriented scale-up / scale-down strategy (POSS) for blown film extrusion allows a flexible adjustment of the mass flow rate as a target process parameter. Consequently, possible processing- and plant-specific restrictions can be considered in practice. Performing an experimental scale-down with a scale-down factor of ten, the feasibility of the POSS could be confirmed. The results demonstrate a good reproducibility of the mechanical properties.

Nevertheless, further studies validating a general applicability of the POSS should be carried out. In this context, more complex products, e.g. barrier films, and rather sensitive materials need to be regarded. Moreover, it would be interesting to use the POSS in the more common direction, performing a scale-up.

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REFERENCES

1. W. Michaeli and J. Hauck, “Up-Scaling experimenteller Untersuchungsergebnisse von Labor- auf Produktionsanlagen,” in *Wertschöpfung bei der Folienextrusion*, edited by VDI-Gesellschaft Kunststofftechnik (VDI-Verlag, Düsseldorf, 1999), pp. 165-199.
2. A. M. Sukhadia, J. Plast. Film Sheet. **10**(3), 213-234 (1994).
3. J. R. A. Pearson, *Mechanics of Polymer Processing* (Elsevier Applied Science Publishers, London, 1985), pp. 508-510.
4. T. Kanai, M. Kimura and Y. Asano, J. Plast. Film Sheet. **2**(3), 224-241 (1986).
5. T. I. Butler, S. Y. Lai and R. Patel, “Scale-up Factors Effecting Crystallization in Polyolefin Blown Film,” in *1994 Polymer, Laminations & Coatings Conference* (TAPPI PRESS, Atlanta, GA, 1994), pp. 289-305.
6. G. J. Schmitz, “Experimentelle Analyse und numerische Modellierung der Deformationsvorgänge bei der Schlauchfolienextrusion,” Ph.D. thesis, RWTH Aachen University, Germany, 1996.
7. F. Ohlendorf, “Vorhersage der mechanischen Folieneigenschaften bei der Schlauchfolienextrusion,” Ph.D. thesis, RWTH Aachen University, Germany, 2004.
8. P. P. Tas, “Film Blowing: From Polymer to Product,” Ph.D. thesis, Eindhoven University of Technology, Netherlands, 1994.

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