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Evaluation of Variational Principle Based Model for LDPE Large Scale Film Blowing Process

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Abstract. In this work, variational principle based film blowing model combined with Pearson and Petrie formulation, considering non-isothermal processing conditions and novel generalized Newtonian model allowing to capture steady shear and uniaxial extensional viscosities has been validated by using experimentally determined bubble shape and velocity profile for LDPE sample on large scale film blowing line. It has been revealed that the minute change in the flow activation energy can significantly influence the film stretching level.

Keywords: Film blowing process, LDPE, Flow activation energy.
PACS: 47.50.-d, 83.10.Gr, 83.50.Uv, 83.60.St, 83.60.Wc, 83.80.Sg

INTRODUCTION

The film blowing process represents technology for production of thin biaxially oriented thermoplastic films, at which take-up force and internal bubble pressure drives orientation in the machine and transverse directions, respectively. Typical applications of blown films include packaging, barrier films, agricultural films, medical films and separators for Li-ion batteries. All these products are mostly made of polyolefines, polystyrene, polyvinylchloride and polyamide [1-3].

In order to understand the complicated relationship between the die design, rheology and processing parameters, modeling of the film blowing process can be very useful. The first film blowing model was developed in 1970 by Pearson and Petrie [4-6] utilizing isothermal processing conditions, a Newtonian model as the constitutive equation, assuming the film as a thin shell in tension and neglecting the effect of inertia, surface tension, air drag, and gravity. This formulation became a basic idea for many researchers (see summarization provided in Muke et al. [7]), such as Pearson and Gutteridge (1978) [8], Cao and Campbell (1990) [9], Liu et al (1995) [10], or in the last years e.g. Muslet and Kamal (2004) [11], Beaulne and Mitsoulis (2007) [12], Sarafrazi and Sharif (2008) [13]. It has been found that the challenging task in the complex film blowing modeling is low stability of the numerical schemes which limits utilization of such models for wide parametric study, which could allow deeper fundamental understanding of the film blowing process. In order to overcome this difficulty, Zatloukal and Vlcek [14] in 2004 developed variational principle based film blowing model at which the process satisfies minimum energy requirements.

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The key feature of the model is availability of analytical equations for the bubble shape, take-up force and internal bubble pressure. Recently, Kolarik and Zatloukal [15] has combined this model with Pearson and Petrie formulation, considering non-isothermal processing conditions and novel generalized Newtonian model [16] as a constitutive equation. By using stable numerical scheme, the model has been validated by using the experimental data obtained on the small laboratory film blowing line.

Main motivation for this work is to firstly evaluate the model capability to describe the large scale film blowing process and secondly to perform the theoretical parametric study in order to understand the role of material/processing conditions on the deformation rates along the bubble. For this purpose, Brampton Engineering film blowing line will be used (see Figure 1).

FIGURE 1. Brampton Engineering air cooled blown film line.

MATHEMATICAL MODELING

Zatloukal-Vlcek Formulation

The variational principle based Zatloukal-Vlcek formulation [14] describes a stable film blowing process as a state when the bubble shape satisfies minimum energy requirements (here the bubble energy is given by the elastic strain energy increase due to take up force and negative work done by the applied internal load). The bubble shape is described by the set of simple analytical equations utilizing four physical parameters: freeze line height, L, bubble curvature, pJ (which is given by membrane compliance, J, and the internal load, p), the die radius, R_0 and the blow up ratio, BUR (the ratio of the final bubble diameter at the freezeline height to the bubble diameter at

the die exit). Here, this model is combined with the Pearson and Petrie formulation, considering non-isothermal processing conditions and novel generalized Newtonian model [16, 17] as a constitutive equation. All mathematical details of the used film blowing modeling are provided in [15].

Constitutive Equation

Non-Newtonian behavior of polymer melts is expressed by the constitutive equation derived by the generalized Newtonian model which was recently proposed in [16, 17]:

$$\tau = 2\eta\left(I_{|D|}, II_D, III_D \right) D \tag{1}$$

where τ express the extra stress tensor, D represents the deformation rate tensor and η stands for the viscosity which varies with the first invariant of the absolute value of deformation rate tensor $I_{|D|} = tr(|D|)$, (where $|D|$ is defined as the square root of D^2) as well as on the second $II_D = 2tr(D^2)$, and third, $III_D = det(D)$, invariants of D according to Eq. 2

$$\eta\left(I_{|\mathrm{D}|}, II_{\mathrm{D}}, III_{\mathrm{D}}\right) = A_1^{\,1-f\left(I_{|\mathrm{D}|}, II_{\mathrm{D}}, III_{\mathrm{D}}\right)} \eta\left(II_{\mathrm{D}}\right)^{f\left(I_{|\mathrm{D}|}, II_{\mathrm{D}}, III_{\mathrm{D}}\right)} \tag{2}$$

where $\eta(II_D)$ is given by the well known Carreau-Yasuda model, Eq. 3, and $f(I_{|D|}, II_D, III_D)$ is given by Eq. 4

$$\eta(II_D) = \frac{\eta_0 a_T}{\left[1 + \left(\lambda a_T \sqrt{II_D}\right)^a\right]^{\left(\frac{1-n}{a}\right)}} \tag{3}$$

$$f\left(I_{|D|}, II_D, III_D\right) = \left\{ tanh\left[\alpha a_T \left(1 + \frac{1}{4\left(\sqrt{3}\right)^3}\right)^{-\psi} \left(\left| 1 + \frac{III_D}{II_D^{3/2}} \right| \right)^{\psi} \frac{\sqrt[3]{4|III_D|} + I_{|D|}}{3} + \beta \right] \frac{1}{tanh(\beta)} \right\}^{\zeta} \tag{4}$$

In these equations, η_0, λ, a, n, α, β, ζ represent adjustable parameters, whereas parameter ψ is equal to 20 (as suggested in [16]) and a_T is temperature shift factor defined according to the Arrhenius equation:

$$a_T = exp\left[\frac{E_a}{R} \left(\frac{1}{273.15 + T} - \frac{1}{273.15 + T_r} \right) \right] \tag{5}$$

where E_a is the activation energy, R the universal gas constant, T_r the reference temperature and T is the local bubble temperature.

EXPERIMENTAL

In this work, coextrusion experiment was carried out on an industrial Brampton Engineering film blowing line for LDPE film production equipped with a 350 mm diameter flat spiral die (R_0 = 0.1626 m) with a die gap of 2.032 mm (Figure 1). During the process, the bubble was cooled by an air ring as well as by an internal bubble cooling system, take-up ratio equal to 7.555 and mass flow rate, 200kg.hr^{-1}. Temperature parameters are provided in Table 1.

TABLE 1. Temperature parameters.

T_{air} (°C)	T_{solid} (°C)	T_{die} (°C)	T_r (°C)	E_a (J·mol^{-1})	R (J·K^{-1}·mol^{-1})	C_p (J·kg^{-1}·K^{-1})
14	105	220	190	55,072	8.314	2,300

The frequency dependent complex viscosity of the LDPE was measured with use of the Advanced Rheometric Expansion System (ARES 2000) rheometer. The transient uniaxial extensional viscosity was measured using the ARES 2000 rheometer equipped with the SER Universal Testing Platform (SER-HV-A01 model) from Xpansion Instruments [18-20]. Cox-Merz rule was applied to estimate shear viscosity versus shear rate from the frequency dependent complex viscosity. Rheological data of the tested LDPE are provided in Figures 2-3 together with the utilized generalized Newtonian model fit having the parameters summarized in Table 2.

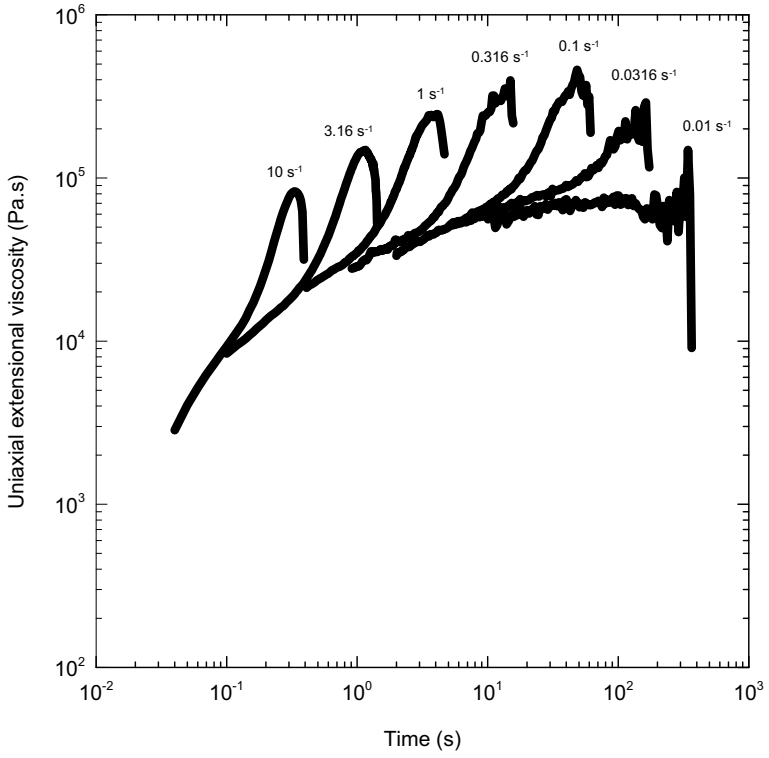

FIGURE 2. Time-dependent uniaxial extensional viscosity $\eta_E^+(t)$ data for LDPE sample obtained by SER at 190°C.

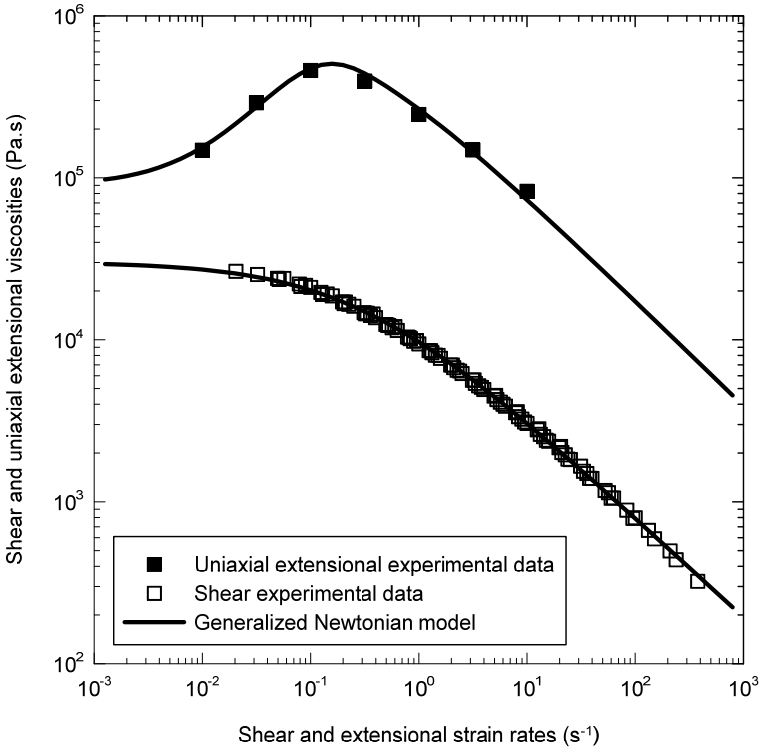

FIGURE 3. Comparison between the utilized generalized Newtonian model fits (solid lines) and measured steady shear and uniaxial extensional viscosities for LDPE sample.

As can be seen in Figure 3, the utilized generalized Newtonian law has very high capability to describe the measured steady-state shear and uniaxial extensional viscosity data for the chosen LDPE sample.

TABLE 2. Generalized Newtonian constitutive equation parameters (A_1=1.2452159.10^{-16}, ψ = 20).

η_0 (Pa·s)	λ (s)	a (-)	n (-)	α (s)	β (-)	ζ (-)
30,251	3.563	0.6396	0.383	8.5469354	0.087847146	0.021594

RESULTS AND DISCUSSION

For the given processing conditions, the experimentally determined bubble shape depicted in Figure 4 was fitted by the film blowing model to obtain the basic parameters, which are summarized in Table 3. For the given bubble shape, the velocity profile along the bubble has been predicted and compared with the corresponding experimental data (see Figure 5). As it can be seen, the agreement between the experimental data and model fit/prediction is reasonably good.

TABLE 3. The Zatloukal/Vlcek film blowing model parameters.

BUR (-)	L (m)	pJ/R_0 (Pa)	R_0 (m)
1.928	0.7118	1.35494836	0.1626

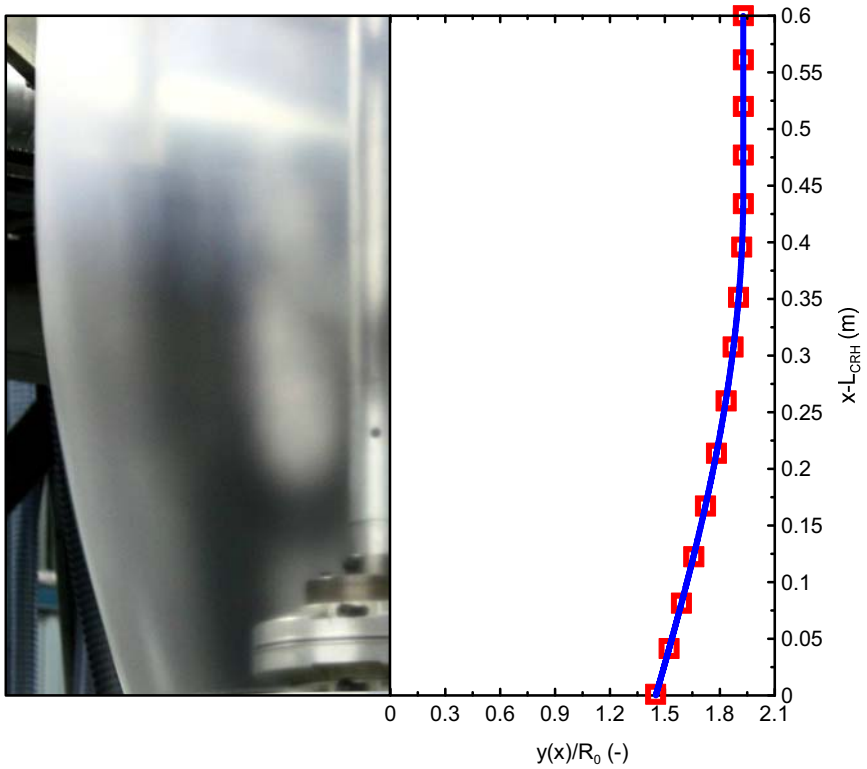

FIGURE 4. Comparison between experimental data (open symbols) and the model fit (solid line) for LDPE bubble shape for given processing conditions.

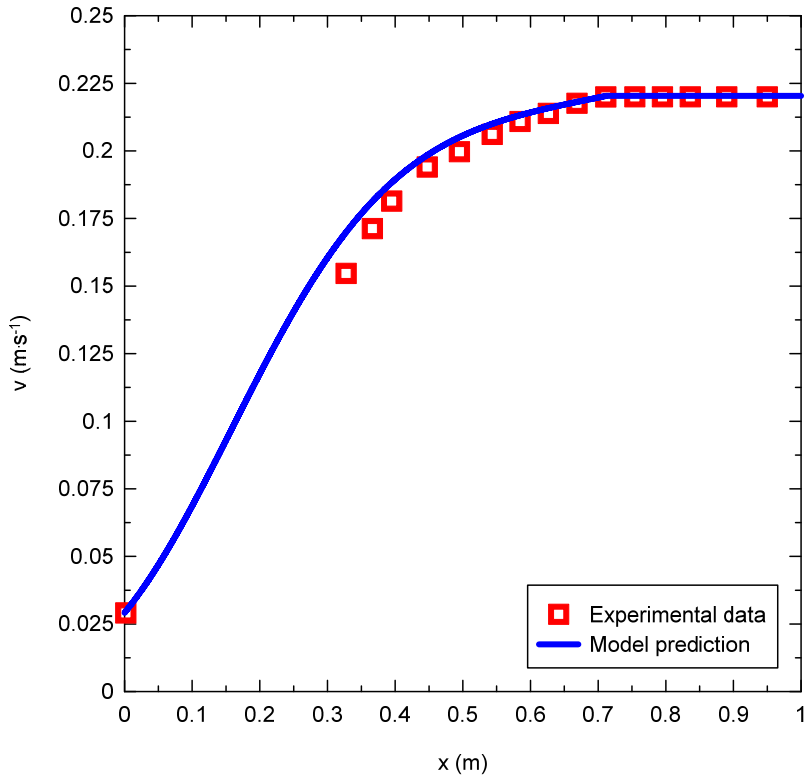

FIGURE 5. Comparison between experimental data (open symbols) and the model prediction (solid line) for LDPE velocity profile.

In the next part of this work, the effect of flow activation energy (10-90 kJ.mol^{-1}) and air cooling temperature (20-100^{o}C) on the velocity, thickness and deformation rate profiles along the bubble was investigated. The results of such analysis are provided in Figures 6-7. It is visible that the flow activation energy has higher effect on bubble deformation rates in comparison with the air cooling temperature. In more detail, the increase in both parameters leads to increase the extensional strain rate in machine and transverse directions which can leads to more intensive and more balanced macromolecular chain alignment, i.e. the final film properties can be significantly improved. This suggests that only the minute change in the flow activation energy (through branching for example) can have significant effect on the stretching level of the film and thus on its final properties.

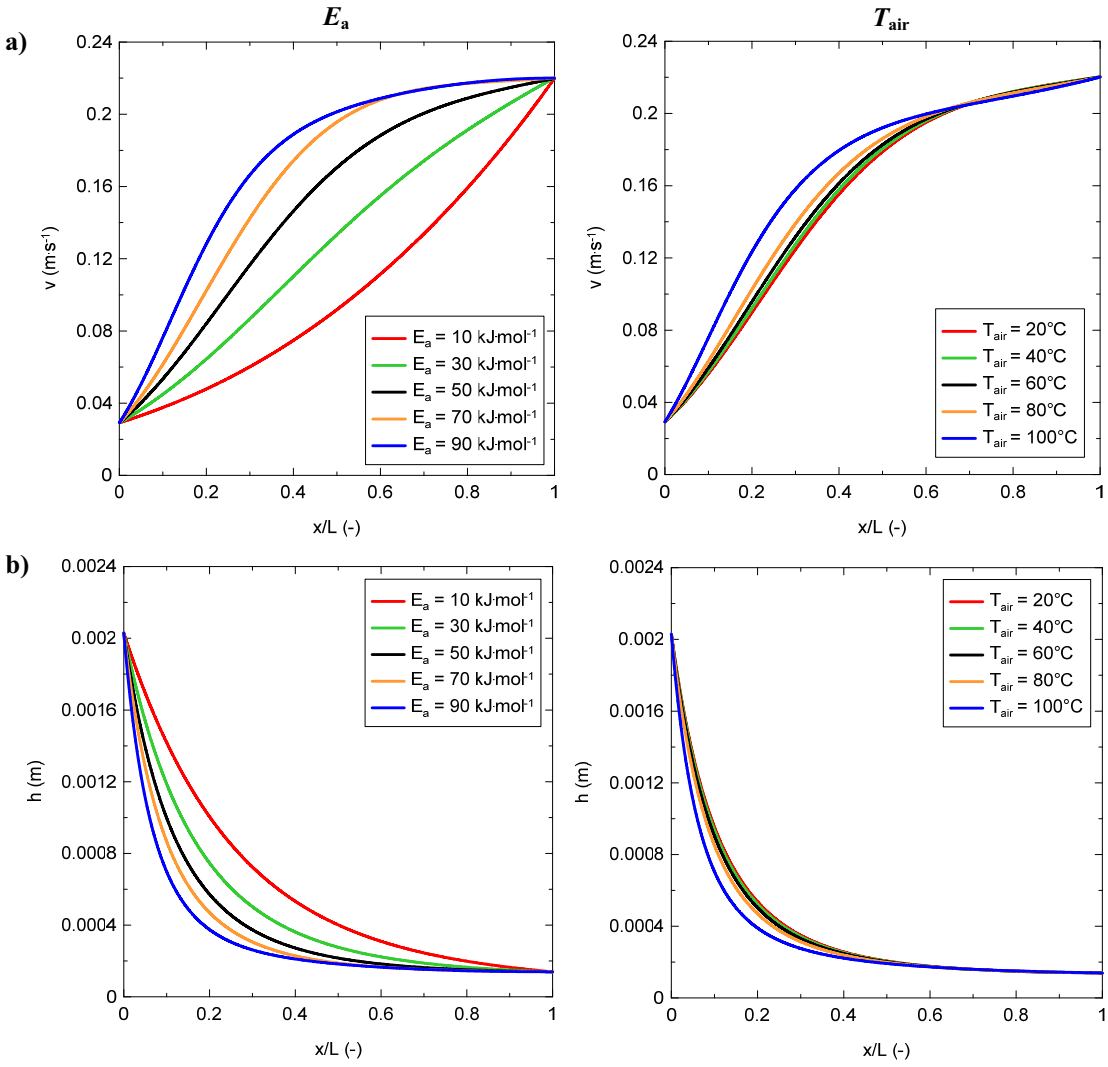

FIGURE 6. Predicted effect of the flow activation energy and air cooling temperature on the **6a)** velocity profile and **6b)** thickness profile.

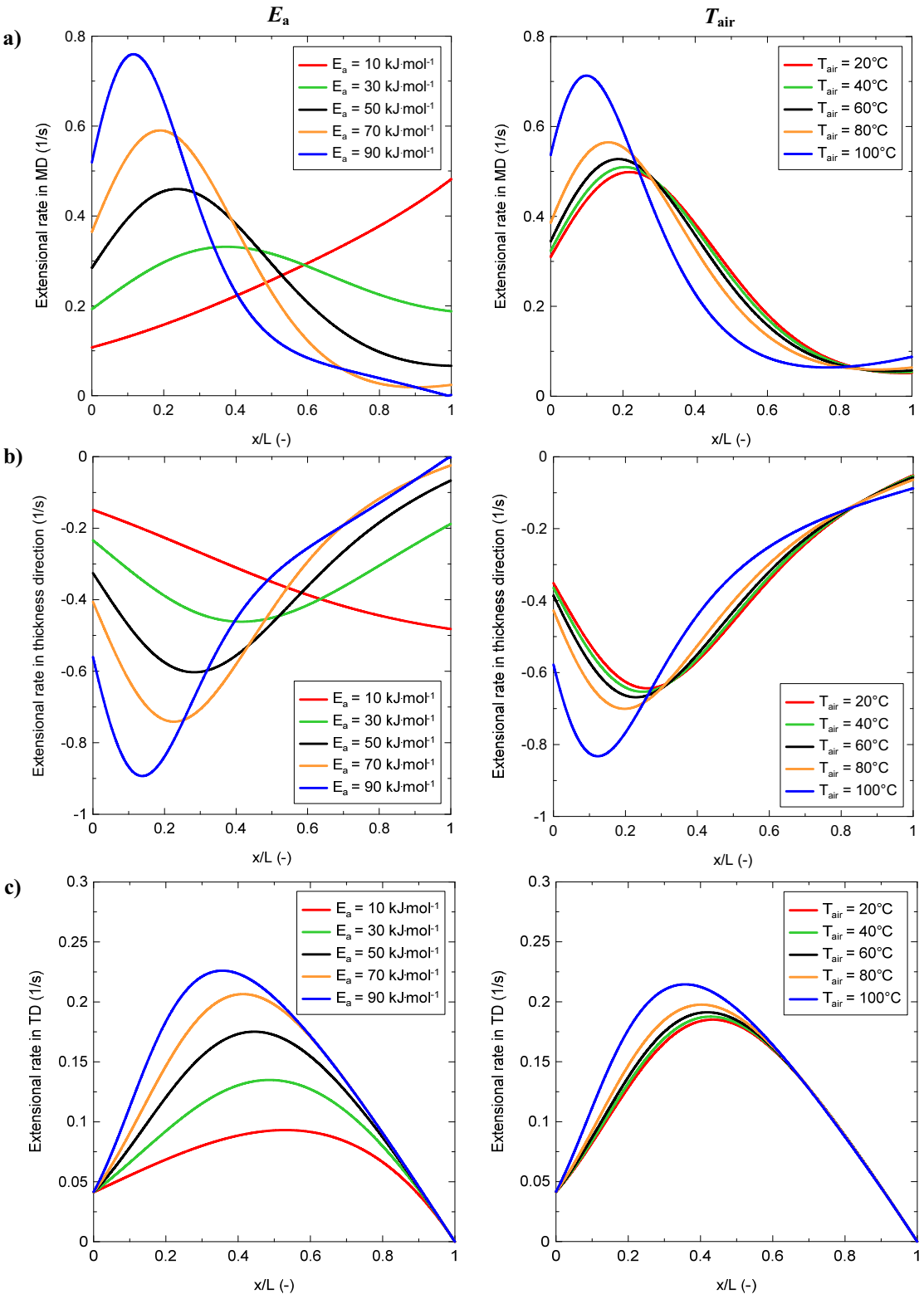

FIGURE 7. Predicted effect of the flow activation energy and air cooling temperature on extensional rates in the **7a)** machine direction, **7b)** thickness direction and **7c)** transverse direction.

CONCLUSION

In this work, variational principle based film blowing model combined with the Pearson and Petrie formulation, considering non-isothermal processing conditions and novel generalized Newtonian model as a constitutive equation has been validated by using large scale film blowing line by using measured LDPE bubble shape and velocity profile. It has been revealed that the minute change in the flow activation energy can significantly influence the film stretching level.

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REFERENCES

1. D. V. Rosato, *Extruding Plastics - A Practical Processing Handbook*, London: Chapman & Hall, 2005, pp. 305-348.
2. K. Cantor, *Blown Film Extrusion*, Munich: Cark Hanser Verlag, 2006, pp. 1-13.
3. T. I. Butler, *Film extrusion Manual: Process, materials, properties*. Atlanta: Tappi press, 2005.
4. J. R. A. Pearson and C. J. S. Petrie, *J. Fluid. Mech.* **40**, 1-19 (1970).
5. J. R. A. Pearson and C. J. S. Petrie, *J. Fluid. Mech.* **42**, 609-625 (1970).
6. J. R. A. Pearson and C. J. S. Petrie, *Plast. Polym.* **38**, 85-94 (1970).
7. S. Muke, H. Connell, I. Sbarski and S. N. Bhattacharya, *J. Non-Newtonian Fluid Mech.* **116**, 113-138 (2003).
8. J. R. A. Pearson and P. A. Gutteridge, *J. Non-Newtonian Fluid Mech.* **4**, 57-72 (1978).
9. B. Cao and G. Campbell, *AIChE J*. **36**, 420–430 (1990).
10. C. C. Liu, D. C. Bogue and J. E. Spruiell, *Int. Polym. Proc.* **10**, 230-236 (1995).
11. I. A. Muslet and M. R. Kamal, *J. Rheol.* **48**, 525-550 (2004).
12. M. Beaulne and E. Mitsoulis, *J. Appl. Polym. Sci.* **105**, 2098-2112 (2007).
13. S. Sarafrazi and F. Sharif, *Int. Polym. Proc.* **23**, 30-37 (2008).
14. M. Zatloukal and J. Vlcek, *J. Non-Newtonian Fluid Mech*. **123**, 201-213 (2004).
15. R. Kolarik and M. Zatloukal, *J. Appl. Polym. Sci.* **122**, 2807-2820 (2011).
16. M. Zatloukal, *J. Non-Newtonian Fluid Mech.* **165**, 592-595 (2010).
17. M. Zatloukal, *Annual Technical Conference - ANTEC, Conference Proceedings* **1**, 92-96 (2011).
18. M. L. Sentmanat, *Rheol. Acta* **43**, 657– 669 (2004).
19. M. L. Sentmanat, U.S. Patent No. 6,578,413 (2003).
20. M. L. Sentmanat, B. N. Wang and G. H. McKinley, *J. Rheol.* **49**, 585-606 (2005).