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Investigation of Heat Transfer in 9-Layer Film Blowing Process by using Variational Principles

Roman Kolarik[a] and Martin Zatloukal[a,b]

[a]Centre of Polymer Systems, University Institute, Tomas Bata University in Zlin, Nad Ovcirnou 3685, 760 01 Zlin, Czech Republic
[b]Polymer Centre, Faculty of Technology, Tomas Bata University in Zlin, nam. T. G. Masaryka 275, 762 72 Zlin, Czech Republic

Abstract. In this work, coextrusion experiments utilizing an industrial 9-layer Brampton Engineering coextrusion film blowing line has been performed under different processing conditions (low/high air cooling intensity) in order to evaluate variational principles based modeling approach using energy equation utilizing variable heat transfer coefficient along the multi-layer bubble. It has been revealed that the variational principle based model can describe the bubble shape and temperature profile reasonably well even if the multi-layer film has been viewed as the static elastic membrane characterized only by one material parameter - bubble compliance *J*, which was not allow to vary along the bubble. Moreover, it has been found that if the freezeline height becomes long, heat transfer coefficient starts to vary significantly along the bubble which has crucial impact on the temperature profile along the multi-layer bubble. The performed theoretical parametric study revealed that increase in blow-up ratio or decrease in bubble curvature and air temperature causing bubble cooling efficiency increases, which allows to cooled down the multi-layer bubble for the given freezeline height to solidification temperature by smaller amount of the air volume flow rate.

Keywords: Polymer, Coextrusion, Multi-layer film blowing, Heat transfer coefficient, Non-isothermal process.
PACS: 47.50.Cd, 83.80.Sg, 83.50.Uv, 44.05.+e, 83.60.St

INTRODUCTION

Coextrusion film blowing is a process at which two or more polymer melts are extruded through a single die, to form a continuous tube which is consequently stretched in machine and transverse directions and simultaneously cooled down by the air to reach required final bubble shape and film properties. Distance between the coextrusion die and polymer melt solidification location is called freezeline hight, it can reach several meters and no bubble deformation takes place above this point. The melt stretching in the transverse direction is predominantly controlled by the blow-up ratio, *BUR*, defined as a ratio of the final bubble diameter at the freezeline height to the die diameter, which usually varies from 1 to 5. In order to control the melt stretching in the axial machine direction, the take-up ratio, *TUR*, is usually kept between 5 and 40 and it is expressed as a ratio between the film velocity above the freezeline height and melt velocity at the die exit [1-4].

In spite of a rapid growth of a blown film coextrusion in the last decades, the number of experimental and modeling studies for this process is very limited [5-12] as

Novel Trends in Rheology V
AIP Conf. Proc. 1526, 107-118 (2013); doi: 10.1063/1.4802606

well as number of works focused on modeling of heat transfer in film blowing process [8,13-20]. In order to extend the knowledge in this area, the main goal of this work is to investigate effect of the heat transfer coefficient on temperature profile along the bubble for multi-layer film blowing process by using variational principles. For the validation purposes, experimental data taken from 9-layer film blowing line have been utilized.

MATHEMATICAL MODELING

Zatloukal-Vlcek Film Blowing Model

The variational principle based Zatloukal-Vlcek model [21] describes film blowing process as a state when the bubble shape satisfies minimum energy requirements. The bubble shape is described by the set of simple analytical equations (see Table 1) utilizing four physical parameters: the freezeline height, L, the bubble curvature, pJ (which is given by the membrane compliance, J, and the internal load, p), the die radius, R_0 and the blow up ratio, BUR.

TABLE 1. Summary of the Zatloukal-Vlcek model equations [21].

Equation type	Equation form	Equation number
Bubble shape	$y = (R_0 - pJ)\cos\left(\frac{x\varphi}{L}\right) - \alpha'(pJ - BURR_0)\sin\left(\frac{x\varphi}{L}\right) + pJ$	(1)
Parameter	$x \in < 0; L >$	(2)
Parameter	$\alpha' = \sqrt{\frac{2pJ - R_0 - BURR_0}{pJ - BURR_0}\left\lvert\frac{R_0(BUR-1)}{pJ - BURR_0}\right\rvert}$	(3)
Parameter	$A = \frac{pJ - R_0}{pJ - BURR_0}$	(4)
Take-up force	$F = -\frac{L^2}{J\varphi^2}$	(5)
Internal bubble pressure	$\Delta p = \frac{pL}{2\pi\int_0^L y\sqrt{1+(y')^2}\,dx}$	(6)

The relationship between the parameter A and φ is provided in Table 2.

TABLE 2. Parameters A and φ for different bubble shapes (y) (adapted from [21]).

Equation	A	φ	y
1.	1	0	R_0
2.	$0 < A < 1$	$arctg\left(\frac{\sqrt{1-A^2}}{A}\right)$	The form of Eq. 1
3.	0	$\pi/2$	$R_0\left\{1 - \sin\left(\frac{x\pi}{2L}\right)(1 - BUR)\right\}$
4.	$-1 < A < 0$	$\pi + arctg\left(\frac{\sqrt{1-A^2}}{A}\right)$	The form of Eq. 1
5.	-1	π	$\frac{R_0}{2}\left\{1 + \cos\left(\frac{x\pi}{L}\right)(1 - BUR) + BUR\right\}$

With the aim to take non-isothermal conditions into account, the simplest version of the cross-sectionally averaged energy equation (the axial conduction, dissipation, radiation effects and crystallization are neglected) is considered here [17, 22]:

$$\dot{m}C_{\mathrm{p}}\frac{dT}{dx} = -2\pi y\left[HTC\left(T - T_{\mathrm{air}}\right)\right] \tag{7}$$

where $\dot{m}$ is the mass flow rate, C_{p} represents the specific heat capacity, T is the bubble temperature, x is the axial position, HTC is the heat transfer coefficient, and T_{air} is the cooling air temperature. Local bubble radius, y, is given by Eq. 1.

The heat transfer coefficient, HTC, in Eq. 7 can be considered as a constant or as a function of the distance from the die, x.

Constant Heat Transfer Coefficient

If the HTC is considered to be constant [22], the Eq. 7 can easily be solved by separation of variables and consequent integration. In order to obtain the equation for the freezeline height, L, the integration has to be done over the whole part of the bubble, i.e. from 0 to L:

$$\int_{T_{\mathrm{die}}}^{T_{\mathrm{solid}}} \frac{\dot{m}C_{\mathrm{p}}}{HTC\left(T - T_{\mathrm{air}}\right)} dT = -2\pi\int_0^L y\,dx \tag{8}$$

where T_{die} and T_{solid} represent the die exit melt temperature, and the solidification temperature of the polymer, respectively. Resulting equation for the freezeline height takes the following form:

$$L = -\frac{1}{2}\dot{m}C_{\mathrm{p}}\ln\left(-\frac{\left(T_{\mathrm{die}} - T_{\mathrm{air}}\right)}{\left(-T_{\mathrm{solid}} + T_{\mathrm{air}}\right)}\right)\cdot$$
$$\cdot\frac{\varphi}{\pi HTC\left(\alpha pJ - \alpha BURR_0 - \sin(\varphi)R_0 - pJ\varphi + \sin(\varphi)pJ - \alpha\cos(\varphi)pJ + \alpha\cos(\varphi)BURR_0\right)} \tag{9}$$

With the aim to get equation for the temperature profile along the bubble, the integration of Eq. 7 has to be generalized i.e. from 0 to arbitrary point at the bubble, x:

$$\int_{T_{\mathrm{die}}}^{T} \frac{\dot{m}C_{\mathrm{p}}}{HTC\left(T - T_{\mathrm{air}}\right)} dT = -2\pi\int_0^x y\,dx \tag{10}$$

After the integration of Eq. 10, the temperature profile along the bubble takes the following analytical expression:

$$T = T_{air} + \left(T_{die} - T_{air}\right)\exp\left\{-\frac{2\pi LHTC}{\dot{m}C_p\varphi}\left(-\alpha\left[R_0BUR - pJ\right]\cdot\left[\cos\left(\frac{x\varphi}{L}\right) - 1\right] + \sin\left(\frac{x\varphi}{L}\right)\left[R_0 - pJ\right] + pJ\varphi\frac{x}{L}\right)\right\} \tag{11}$$

Variable Heat Transfer Coefficient

Here, the equation, developed by Muslet and Kamal [20] based on Sidiropoulos approach [23], describing variation of the heat transfer coefficient along the bubble, was utilized:

$$HTC_{\mathrm{var}} = C_{\mathrm{S}} \frac{560 - 780\exp\left(-1.27\left(T_{\mathrm{f}} - T_{\mathrm{air}}\right) - 0.035y\right)}{1 + \exp\left(0.5L - x\right)} + \Omega \tag{12}$$

where $\Omega = A_{\mathrm{S}} \exp\left(-x^2\right) + B_{\mathrm{S}}$, $A_{\mathrm{S}} = 6Q_{\mathrm{air}} + 30$, $B_{\mathrm{S}} = 1.4Q_{\mathrm{air}} + 7.4$, $C_{\mathrm{S}} = 0.084Q_{\mathrm{air}}$.

As can be seen, the variable heat transfer coefficient, HTC_{var}, depends on the temperature difference between the film surface, T_{f}, and the cooling air temperature, T_{air}, on the bubble radius, y, freezeline height, L, particular distance from the die exit, x, and the volumetric flow rate of the cooling air, Q_{air}, in liters per second.

In this case, the temperature profile along the bubble was obtained by application of 4th order Runge-Kutta numerical scheme on the energy equation defined by Eq. 7 utilizing Eq. 12 for variable heat transfer coefficient.

EXPERIMENTAL

In this work, coextrusion experiments were carried out on an industrial 9-layer Brampton Engineering coextrusion film blowing line (Figure 1) equipped with a 350 mm diameter flat spiral die (R_0 = 0.1626 m) with a die gap of 2.032 mm (H_0 = 0.002032 m). During the process, the bubble was cooled by an air ring as well as by an internal bubble cooling system. The coextruded structure was LDPE/LDPE/tie/PA6/EVOH/PA6/tie/LDPE/LDPE with following layer thicknesses: 17.5 % for LDPE, 5% for tie, 5% for PA6 and 10% for EVOH. In both experiments, where low and high air cooling intensity was investigated, the following parameters were kept to be constant: die exit temperature, T_{die} = 250°C, overall film thickness (gauge), H_1=100 μm, (which corresponds to draw-down ratio DDR = 11.17), blow-up ratio, BUR = 1.82, lay-flat film, 1000 mm, internal bubble pressure, Δp = 489 Pa, and constant overall mass flow rate, 300 kg.hr^{-1}, (i.e. constant line speed 25.9 m.min^{-1}).

For given processing conditions, the bubble shape was monitored by the EOS digital SLR photo camera Canon EOS 450D model (Canon, Inc., Japan) with resolution of 12.2 Mpx equipped with Canon lens EF-S 18-55mm f/3.5-5.6 IS whereas the average bubble temperature was measured by the heat gun, model camera: INFRACAM^{TM} using calibration site FLIR SYSTEM, AB SWEDEN and corresponding software (ThermaCAM QuickReport 1.0).

FIGURE 1. Brampton Engineering 9-layer air cooled blown film line.

FILM BLOWING MODEL VALIDATION

In order to test whether the utilized film blowing model can describe the bubble shape and temperature profile during the coextrusion film blowing process for two different air cooling intensity, firstly, the three unknown film blowing model parameters L, BUR and pJ (for the known die radius R_0 = 0.1626 m) were determined through fitting of two experimentally obtained bubble shapes by Eq. 1 utilizing the least square minimization method. In the second step, by keeping the L, BUR, pJ, R_0, C_p and $\dot{m}$ fixed, the measured temperature profiles were fitted by Eq. 11 and Eq. 7 + Eq. 12 considering constant and variable HTC, respectively, in order to find out T_{air}, T_{solid}, Q_{air} model parameters. All model parameters are summarized in Table 3. The comparison between the experimentally determined bubble shapes and temperature profiles for the tested processing conditions are summarized in Figures 2-3 and as can be seen, the agreement between the measured data and model fits is very good. In more detail, the model can describe the bubble shape as well as temperature profile along the bubble reasonably well for two different air cooling intensity under highly non-isothermal conditions, even if the assumption about the constant bubble compliance J along the multi-layer bubble has been used. The fact that the single parameter J works could be explained by the statement that the layers which freezes first in coextrusion dictates the bubble shape [24,25].

TABLE 3. Summarization of model parameters for both experiments performed on industrial 9-layer Brampton Engineering coextrusion film blowing line.

Air ring	Low cooling	High cooling
BUR **(-)**	1.79554	1.79934
pJ/R $_0$ **(-)**	1.06416160	1.35021986
L **(m)**	0.75704	0.55305
T_{air} **(°C)**	125	110
T_{solid} **(°C)**	139	130
Q_{air} **(l·s^{-1})**	10.866	13.591
$\dot{m}$ **(kg.hr^{-1})**	300	300
C_p **(J·kg^{-1}·K^{-1})**	2300	2300

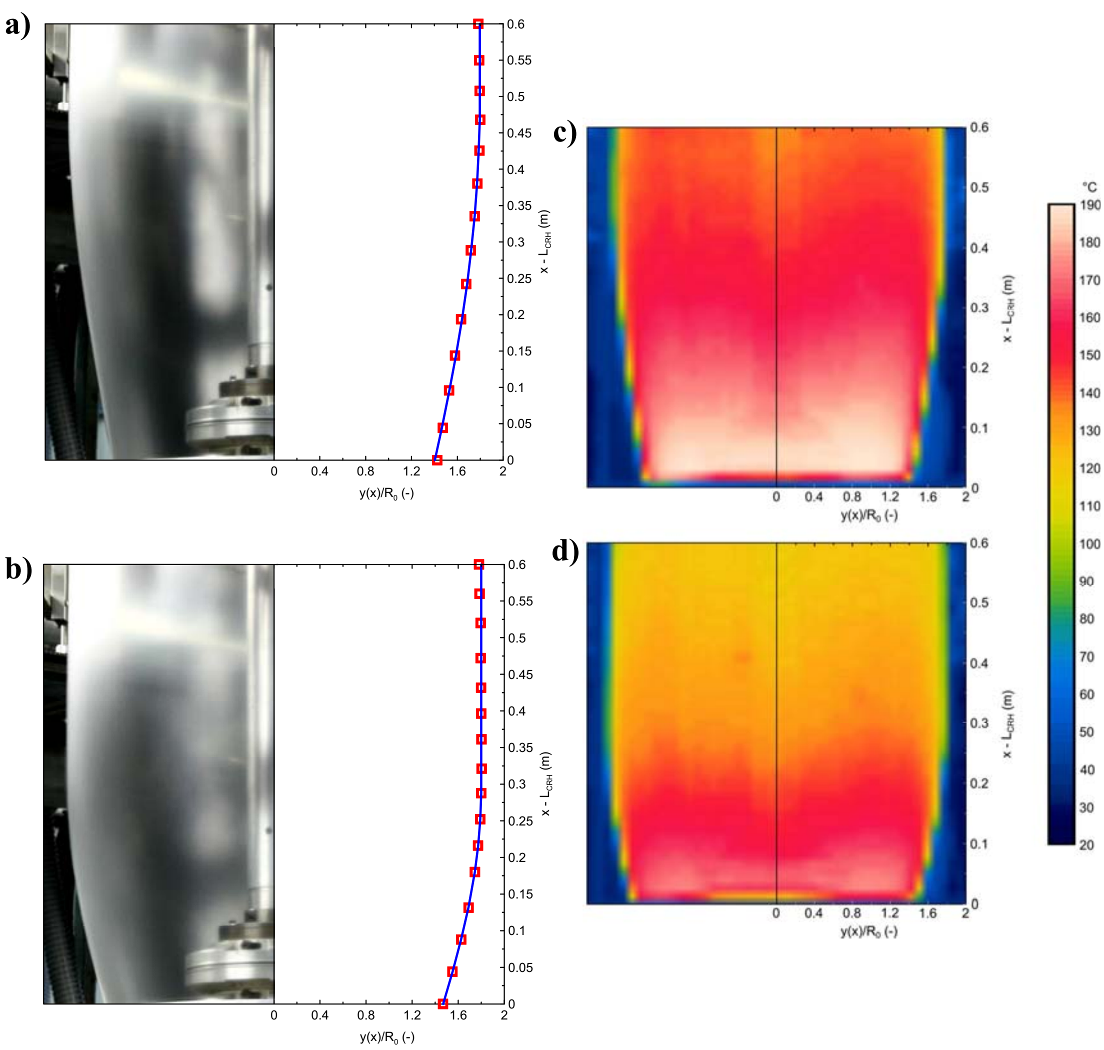

FIGURE 2. Comparison between experimentally determined multi-layer bubble shape (open symbols) and model prediction (line) for mass flow rate equal to 300 kg.hr^{-1} (cooling ring height, L_{CRH} = 0.26 m), for **2a)** low air cooling intensity and **2b)** high air cooling intensity. The effect of air bubble cooling intensity on the average multi-layer bubble temperature field at fixed mass flow rate equal to 300 kg.h^{-1} (cooling ring height, L_{CRH} = 0.26 m) for **2c)** low air cooling intensity and **2d)** high air cooling intensity.

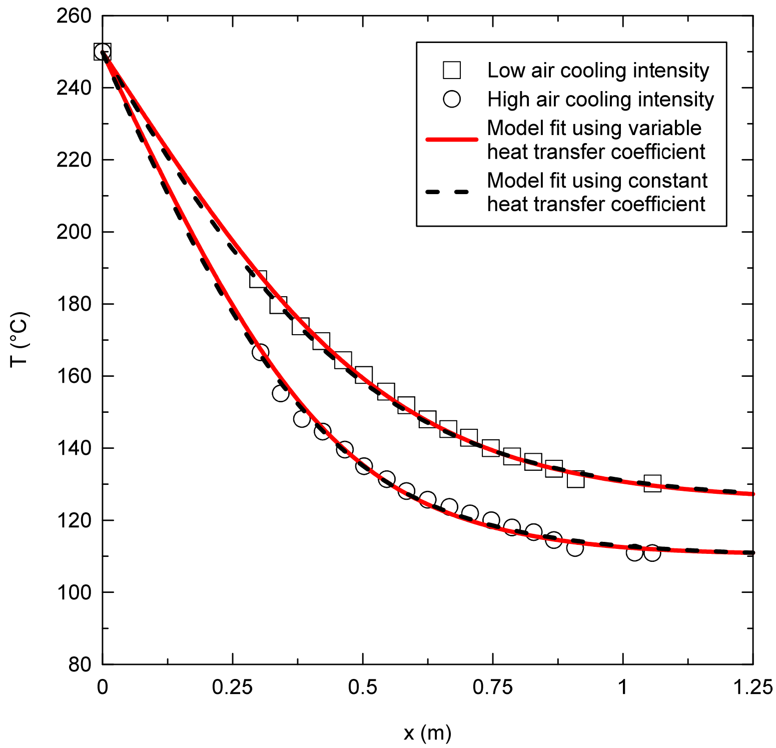

FIGURE 3. Comparison between experimentally determined multi-layer bubble temperature profiles taken from the bubble centre (open symbols) and model fits (lines) using constant/variable heat transfer coefficient for low and high air cooling intensities and fixed mass flow rate equal to 300 $kg.hr^{-1}$.

THEORETICAL PARAMETRIC STUDY

Firstly, the effect of constant versus variable *HTC* definition on the temperature profile prediction for bubbles having different freezeline height was investigated for given processing conditions (see Table 4) and the results are depicted in Figure 4. It is visible that for the bubble with short freezeline hight the temperature profile predictions for constant/variable *HTC* are comparable which can be explained by relatively small variation of *HTC* along the short bubble as visible in Figure 4 (left side). On the other hand, if the freezeline height becomes long, *HTC* starts to vary significantly along the bubble (high value at the die, low value at the freezeline). In such a case, utilization of constant *HTC* may leads to rather erroneous overprediction of the bubble temperature as it is shown in Figure 4 (right side).

TABLE 4. Summarization of the model parameters for two different freezeline heights.

	High cooling	**Low cooling**
***BUR* (-)**	4.5	4.5
pJ/R_0 (-)	2.75	2.75
***L* (m)**	1.0	3.0
C_p ($J \cdot kg^{-1} \cdot K^{-1}$)	2300	2300
T_{air} (°C)	25	25
T_{solid} (°C)	131	131
Q_{air} ($l \cdot s^{-1}$)	0.798	0.172

Secondly, the effect of the blow-up ratio, *BUR*, the freezeline height, *L*, the bubble curvature, pJ/R_0, and the air cooling temperature, T_{air}, on the cooling efficiency was investigated considering variable heat transfer coefficient. For such a purpose, each of them was systematically varied, whereas the other parameters were kept the same, in order to find out the *HTC* and temperature profiles along the bubble as well as air volume flow rate, Q_{air}, needed to cool down the bubble to reach T_{solid} for the given freezeline height. Results of the theoretical analysis are provided in Table 5 and Figures 5 and 6. It is nicely visible that if *BUR* and *L* increases or pJ/R_0 and T_{air} decreases the bubble cooling efficiency increases which leads to decrease in air volume flow rate to cool down the bubble for the given freezeline height.

TABLE 5. Summarization of the volumetric flow rates of the cooling air, Q_{air}, (included in Eq. 12) for all theoretically investigated processing conditions.

	BUR **(-)**			***L*** **(m)**			***pJ/R₀*** **(-)**			T_{air} **(°C)**		
Value	1.5	3.0	4.5	1	2	3	0	1.88	2	25	75	125
Q_{air} **(l·s⁻¹)**	2.26	1.11	0.64	2.37	1.11	0.69	0.45	0.53	0.63	0.53	1.11	3.97

CONCLUSION

In this work, coextrusion experiments utilizing an industrial 9-layer Brampton Engineering coextrusion film blowing line for LDPE/LDPE/tie/PA6/EVOH/PA6/tie/LDPE/LDPE film production has been performed under different processing conditions (low/high air cooling intensity) in order to evaluate variational principles based modeling approach using energy equation utilizing variable heat transfer coefficient along the multi-layer bubble.

It has been revealed that the variational principle based model can describe the bubble shape and temperature profile reasonably well for both, decreased/increased freeze line height due to increased/decreased air cooling intensity under highly non-isothermal conditions even if the multi-layer film has been viewed as the static elastic membrane characterized only by one material parameter - bubble compliance *J*, which was not allow to vary along the bubble. Moreover, it has been found that if the freezeline height becomes long, *HTC* starts to vary significantly along the bubble (high value at the die, low value at the freezeline) which has crucial impact on the temperature profile along the bubble in comparison with the short bubbles for which the heat transfer coefficient variation is low. The performed theoretical parametric study revealed that increase in *BUR* and *L* or decrease in bubble curvature and T_{air} causing bubble cooling efficiency increases, i.e. the bubble can be cooled down to the solidification temperature for the given *L* by the smaller amount of the air volume flow rate. Based on this work, it is believed, that the variational principle based modeling approach can be used and explored for the multi-layer film blowing process to understand complex rheological, heat transfer and crystallization phenomena occurring in multi-layer film blowing process with respect to process stability and final film properties.

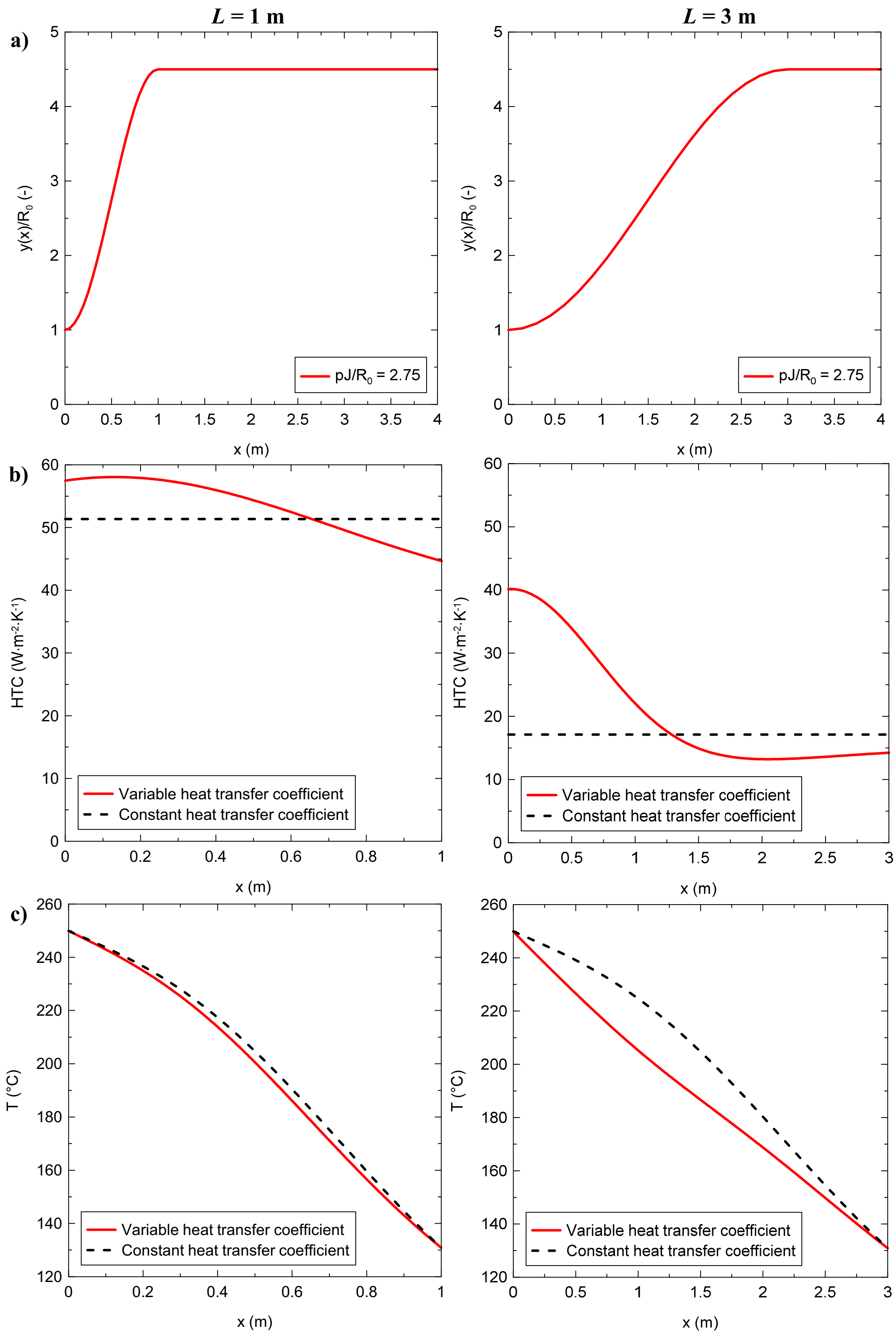

FIGURE 4. Theoretical investigation of the constant and variable heat transfer coefficient effect in multi-layer film blowing process for processing conditions T_{air} = 25°C, pJ/R_0 = 2.75, BUR = 4.5, for bubbles with different levels of freezeline height, L = 1 m (left column) and L = 3 m (right column), where **4a)** presents bubble shapes, **4b)** constant/variable heat transfer coefficient effect along the bubble, and **4c)** presents temperature profiles.

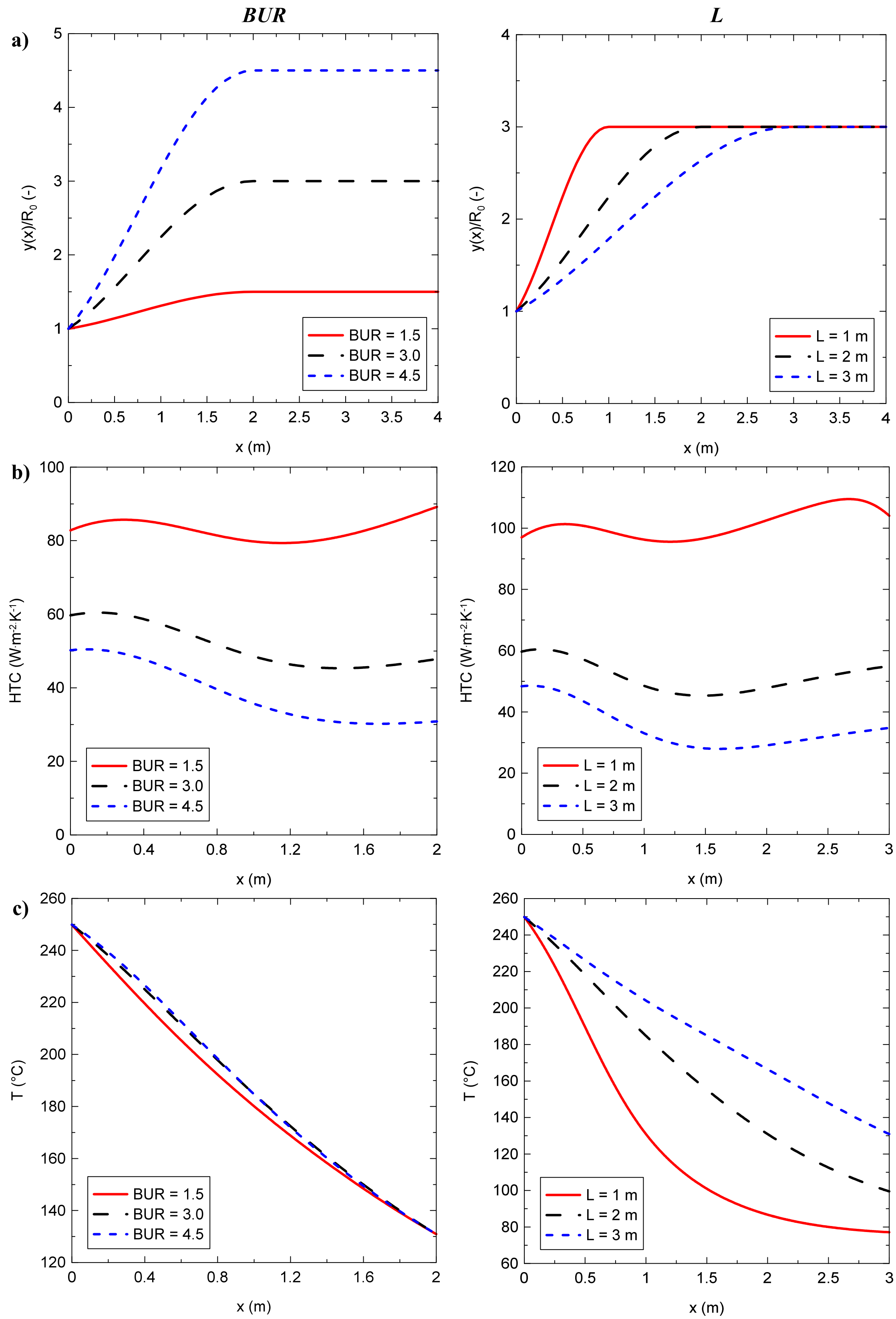

FIGURE 5. Theoretical investigation of the variable heat transfer coefficient effect in multi-layer film blowing process for processing conditions T_{air} = 75°C, L = 2 m, BUR = 3, pJ/R_0 = 1.88, and for different levels of blow-up ratio, BUR and freezeline height, L, affecting the **5a)** bubble shape, **5b)** variable heat transfer coefficient and **5c)** temperature profile along the bubble.

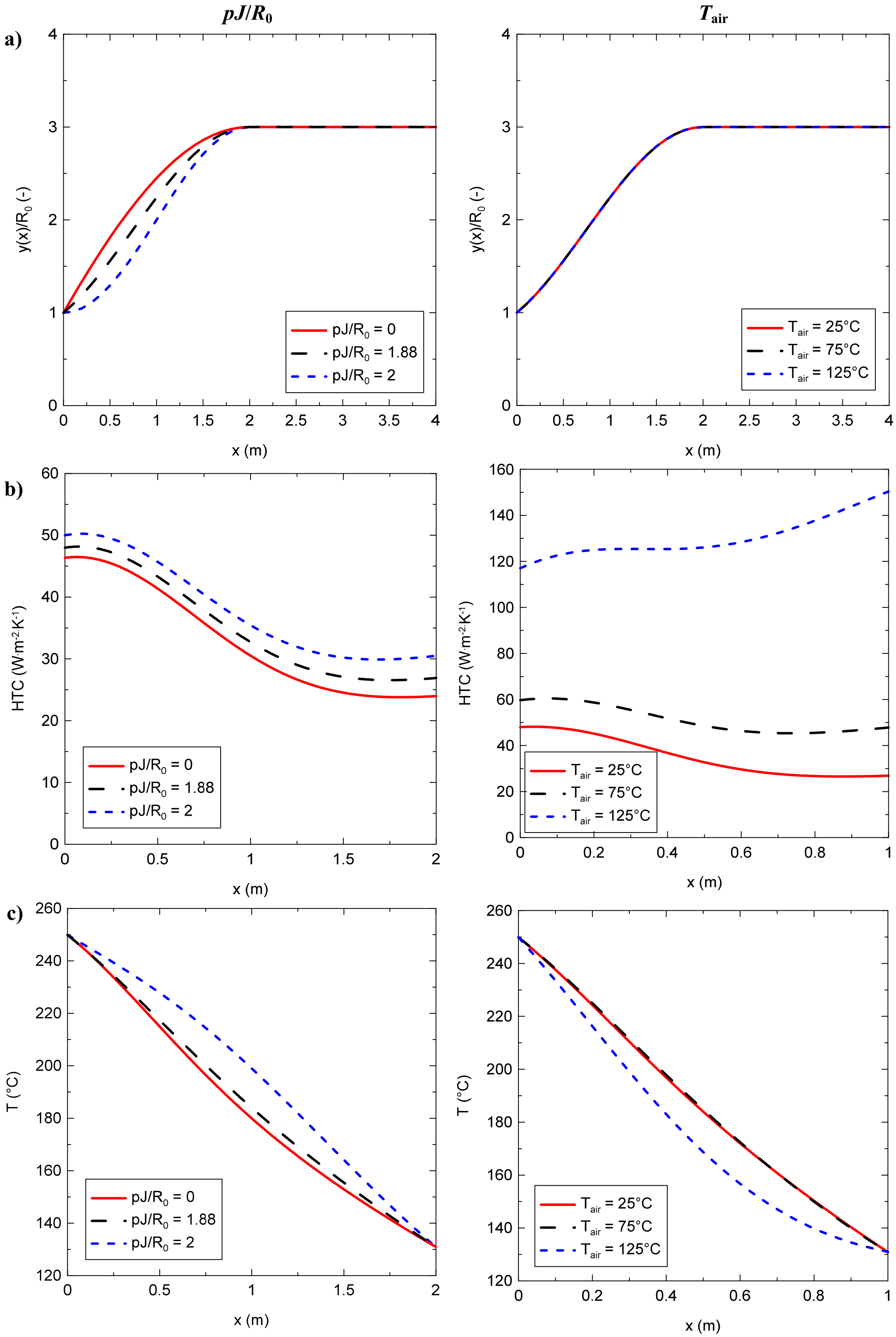

FIGURE 6. Theoretical investigation of the variable heat transfer coefficient effect in multi-layer film blowing process for processing conditions T_{air} = 75°C, L = 2 m, BUR = 3, pJ/R_0 = 1.88, and for different levels of bubble curvature, pJ/R_0, and air cooling temperature, T_{air}, affecting the **6a)** bubble shape, **6b)** variable heat transfer coefficient and **6c)** temperature profile along the bubble.

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REFERENCES

1. T. I. Butler, *Film extrusion Manual: Process, materials, properties*, Atlanta: Tappi press, 2005.
2. M. Zatloukal and J. Vlcek, *J. Non-Newtonian Fluid Mech.* **133**, 63-72 (2006).
3. D. G. Baird and D. I. Collias, *Polymer Processing: Principles and Design*, New York: John Wiley & Sons, Inc., 1998.
4. M. Beaulne and E. Mitsoulis, *J. Appl. Polym. Sci.* **105**, 2098-2112 (2007).
5. C. D. Han and R. Shetty, *Polym. Eng. Sci.* **18**, 187-199 (1978).
6. K.-S. Yoon and C.-W. Park, *Polym. Eng. Sci.* **32**, 1771-1777 (1992).
7. K.-S. Yoon and C.-W. Park, *J. Non-Newtonian Fluid Mech.* **89**, 97-116 (2000).
8. J. Stasiek, *Prog. Rubber Plast. Recycl. Technol.* **16**, 183-192 (2000).
9. S. Elkoun, M. A. Huneault, K. McCormick, F. Puterbaugh and F. Kale, *Polym. Eng. Sci.* **45**, 1222-1230 (2005).
10. E. Gamache, J.-F. Agassant, Y. Demay and P. G. Lafleur, *J. Plast. Film Sheeting* **21**, 127-144 (2005).
11. G. Gururajan and A. A. Ogale, *J. Plast. Film Sheeting* **23**, 37-49 (2007).
12. F. Xu and A. J. McHugh, *Chem. Eng. Sci.* **64**, 4787-4795 (2009).
13. T. Kanai and J. L. White, *J. Polym. Eng.* **5**, 135-157 (1985).
14. C. D. Han and J. Y. Park, *J. Appl. Polym. Sci.* **19**, 3277-3290 (1975).
15. H. A. Khonakdar, J. Morshedian and A. O. Nodehi, *J. Appl. Polym. Sci.* **86**, 2115-2123 (2002).
16. C. C. Liu, D. C. Bogue and J. E. Spruiell, *Int. Polym. Proc.* **10**, 230-236 (1995).
17. A. K. Doufas and A. J. McHugh, *J. Rheol.* **45**, 1085-1104 (2001).
18. B. Cao and G. Campbell, *AIChE J.* **36**, 420-430 (1990).
19. S. Sarafrazi and F. Sharif, *Int. Polym. Proc.* **23**, 30-37 (2008).
20. I. A. Muslet and M. R. Kamal, *J. Rheol.* **48**, 525-550 (2004).
21. M. Zatloukal and J. Vlcek, *J. Non-Newtonian Fluid Mech*. **123**, 201-213 (2004).
22. R. Kolarik and M. Zatloukal, *J. Appl. Polym. Sci.* **122**, 2807-2820 (2011).
23. V. Sidiropoulos, "The Effects of Air Cooling on the Film Blowing Process", Ph.D. thesis, McMaster University, 2000.
24. B. A. Morris, *J. Plast. Film Sheet.* **15**, 25-36 (1999).
25. G. Giriprasath and A. A. Ogale, *Annual Technical Conference – ANTEC, Conference Proceedings* **2**, 830-834 (2006).