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FORMATION OF THE NECK IN THE TUBULAR POLYMER FILM PRODUCED BY BLOW-MOLDING EXTRUSION

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ABSTRACT

By increasing the rate of extrusion of the polymer, tubular film area of the bubble neck formation increases. This leads to the accumulation of large recoverable strain in the bi-axially oriented thermo-shrinkable tubular polymer film. The formation of the bubble neck is characterized by kinematic, dynamic, rheological and thermal energy parameters, which influence each other. Based on theoretical and experimental studies the relationship between these parameters established which makes it possible to influence the properties of the producing films, in particular on their strength properties. Also, the mechanism of transition from the molding in tubular film process with no necking at low speeds compared to the same extrusion process to form a neck at high rates of extrusion is presented.
Keywords: *extrusion, tubular polymer film, bubble neck, parameters*

1. INTRODUCTION

The gradual increase in the rate of extrusion of tubular polymer film obtained by the blowing method leads to a formingof a bubble neck [1],[3],[4],[5]. There have been numerous publications devoted to the polymer tubular film blow-molding problem [1],[2],[3],[4],[5],[6], but there are still insufficient information related to the phenomenon of formation of a polymer tubular film neck [1],[6].
On the high-efficiency process level, the longitudinal(axial) and transversal (hoop) stretching of the film bubble above the necking area has been state-of-the-art through application of the tubular film inflation under air pressures inside the thin film tubing [1],[3],[4],[5].
The latest works describing process of reception of a blown film, do not give proper attention to extrusion process at its transition to a mode of formation of a neck [1],[2],[4]. At the same time, considering that strength properties of received films essentially depend on their degree of

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orientation, and also on orientation parity in axial (longitudinal) and tangential (transversal) directions, there is a necessity for a numerical estimation of elastic properties of the shrinkable polymeric films produced by blown extrusion method.
The purpose of this paper is to analyze the mechanism of formation of the tubular polymer film neck whose understanding will allow properties prediction of the received film.

2. BACKGROUND AND DEFINITIONS

As a choice of polymer for studying of blowing films process various types of polyethylene are usually accepted [1],[2],[3],[4],[5],[6]. Scheme of blowing films process is presented on Fig. 1.
Until recently only local parameters of the film along an extruder die axis have been investigated theoretically and experimentally [2],[3],[5]. It has lead to considerable complication of calculation methods of tubular films production and, thus, to considerable difficulties of the account of mutual influence of various parameters of the process. Thus, the published results cannot be used for working out of the approach describing the mechanism of formation of a neck in an area of the bubble formation.
As blow up ratio in the neck formation area at formation of the bubble is absent (or nearly absent), necks blow up ratio B_n in this case will be close to unit.It is logical to define the blowing mechanism of the tubular film as a uniform bi-axiallly drawing..Following the assumption that drawing ratio λ_{1B} in the blowing area is equal to blow up ratio $B = \lambda_{2B}$, the analysis of key parameters of blowing formation of the tubular polymeric films is presentedin this paper .

3. KINEMATICS OF THE TUBULAR FILM EXTRUSION

Diameters of the cooled tubular film can be calculated as:

$$D_f = 2A\pi^{-1} \tag{3.1}$$

where A is a width of tubular film in packed up form, m. The extruder volume output can be determined as:

$$q_v = A\delta_f v_f \tag{3.2}$$

where v_f is the take up speed of the cooled tubular film at the cold end of the extrusion line, m/s.
The mean polymer melt outlet velocity from the annular die is equal:

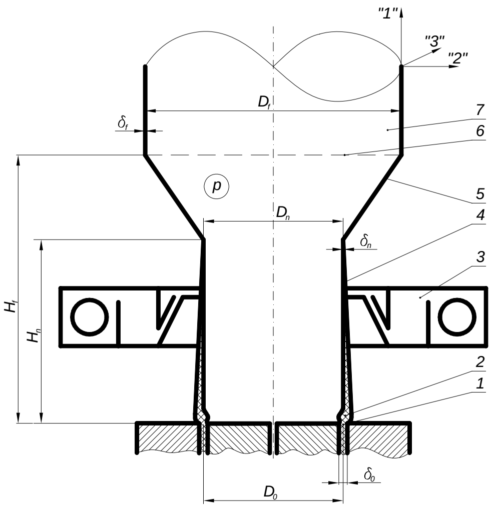
$$v_0 = q_v \rho_f (\pi D_0 \delta_0 \rho_m)^{-1} \tag{3.3}$$

where ρ_f and ρ_m are densities of the cooled and melted polymers, respectively, kg/m^3.
The total draw ratio of the tubular film in the "1" and "2" directions can be determined by expressions (3.4) and (3.5), respectively:

$$\lambda_1 = v_f v_0^{-1} \tag{3.4}$$

$$\lambda_2 = D_f D_0^{-1} \tag{3.5}$$

where v_0 is the mean polymer melt outlet velocity from annular die, m/s.



D_f, δ_f – diameter and thickness of the cooled tubular film, respectively, m; D_n, δ_n – diameter and thickness of the bubble neck in the upper cross-section, respectively, m; H_f, H_n – the freeze line height and the bubble neck length, respectively, m; D_0, δ_0 – mean values of diameter and thickness of the annular drawing die, respectively, m; p – air pressure inside the bubble, Pa;
1 – annular die outlet; 2 – die swell; 3 – blower cooling ring; 4 – bubble neck; 5 – film inflation area; 6 – freeze line; 7 – cooled tubular film;
"1" is the machine direction; "2" is the radial direction; "3" is the transversal direction in a Cartesian coordinate frame

Fig.1 – The film-blowing process scheme

The total Hencky's deformations [7],[8],[9] of the tubular film in the "1" and "2" directions can be determined by expressions (3.6) and (3.7), respectively:

$$\varepsilon_1^H = \ln \lambda_1 \tag{3.6}$$

$$\varepsilon_2^H = \ln \lambda_2 \tag{3.7}$$

The recoverable elastic Hencky's deformation of the tubular film in the "1", "2" and "3" directions can be defined by equation (3.8), (3.9) and (3.10), respectively:

$$\varepsilon_{1e}^H = \ln\left(\frac{l_f}{l_t}\right); \varepsilon_{2e}^H = \ln\left(\frac{b_f}{b_t}\right); \varepsilon_{3e}^H = \ln\left(\frac{\delta_f}{\delta_t}\right) \tag{3.8}$$

where l_f, b_f, δ_f are length, width and thickness of the cooled film specimen, respectively, m; l_t, b_t, δ_t are length, width and thickness of these specimen after heat treatment, respectively, m. In the first approximation the total Hencky's rate-of-strain in the "1" direction can be computed in the following manner [8]

$$\dot{\varepsilon}_1^H = (v_f - v_0) H_f^{-1} \tag{3.9}$$

The time of forming the film bubble can be determined by the following equation:

$$t_f = \varepsilon_1^H \left(\dot{\varepsilon}_1^H\right)^{-1} \tag{3.10}$$

A weight of the film bubble can be calculated by:

$$G_f = t_f q_v \rho_f g \tag{3.11}$$

where g is free fall acceleration, m/s^2. The freeze line height H_f can be determined depending on the [8]

$$H_f = (v_f - v_0)\left(\dot{\varepsilon}_1^H\right)^{-1} \tag{3.12}$$

Assuming that full speed of deformation $\dot{\varepsilon}_1^H$ in a formation area does not change, by analogy to dependence (3.12) we will receive expression of local speed v_n in the top section of a neck:

$$v_n = v_f - H_n \dot{\varepsilon}_1^H \tag{3.13}$$

If the blowup ratio B_n of bubble neck will be equal to unity, the thickness δ_n in the upper cross section of neck can be determined by the following expression:

$$\delta_n = q_v \rho_f \left(\pi D_n v_n \rho_0\right)^{-1} \tag{3.14}$$

where v_n is the speed in upper cross section of neck, m/s.

In the second approximation the mean Hencky's rate-of-strain $\dot{\varepsilon}_{1B}^H$ in the "1" direction on the blowup area of the film bubble can be computed as follows

$$\dot{\varepsilon}_{1B}^H = \left(v_k - v_n\right)\left(H - H_n\right)^{-1} \tag{3.15}$$

where v_k is the take up speedof the cooled tubular film, m/s ($v_k = v_f$).

The Hencky's strain of the film bubble on the blowup area in the "1" direction can be determined as:

$$\varepsilon_{1B}^H = \ln\left(v_k v_n^{-1}\right) \tag{3.16}$$

In such a situation, a film bubble blowup time can be calculated as follows:

$$t_B = \varepsilon_{1B}^H \left(\dot{\varepsilon}_{1B}^H\right)^{-1} \tag{3.17}$$

Average speed of Hencky'sdeformation in a direction "2"in the blowing area is defined as:

$$\dot{\varepsilon}_{2B}^H = t_B^{-1} \cdot \ln \lambda_{2B} \tag{3.18}$$

Thus time of formation of a neck t_n is more exact and can be calculated by:

$$t_n = t_f - t_B \tag{3.19}$$

Kinematic parameters are presented in Table 1.

Table 1: Kinematic parameters of the tubular film extrusion

Number of Equation	Symbol	Dimension	Number of tubular film					
			1	2	3	4	5	6
	v_f	cm/s	6.7	10	13.3	16.7	20	30
	H_f	cm	20	24	55	67	77	87
	H_n	cm	0	0	36	42	52	58
	A	cm	36.5	36	34	39	40	38
	δ_f	mm	0.12	0.12	0.09	0.08	0.06	0.0365
3.1	D_f	cm	22.9	22.9	21.7	24.8	25.5	24.2
3.2	q_v	cm^3/s	5.75	8.64	8.17	10.4	9.6	8.0
3.3	v_0	cm/s	2.6	3.9	3.7	4.6	4.34	3.6
3.4	λ_1	-	2.6	2.6	3.6	3.6	4.6	8.3
3.5	λ_2	-	2.29	2.29	2.17	2.48	2.55	2.42
3.6	ε_1^H	-	1.03	0.92	1.28	1.27	1.53	2.12
3.7	ε_2^H	-	0.83	0.83	0.77	0.91	0.94	0.88
3.8	ε_{1e}^H	-	1.2	1.38	1.7	1.9	1.6	1.8
3.8	ε_{2e}^H	-	0.7	0.47	0.5	0.76	0.8	0.24
3.8	ε_{3e}^H	-	-1.9	-1.85	-2.2	-2.66	-2.4	-2.0
3.9	$\dot{\varepsilon}_1^H$	s^{-1}	0.2	0.254	0.175	0.18	0.2	0.3
3.10	t_f	s	4.5	3.6	7.3	7.0	7.6	7.0
3.11	G_f	N	0.23	0.25	0.48	0.58	0.58	0.45
3.13	v_n	cm/s	-	-	7.0	9.14	9.6	12.6
3.14	δ_n	mm	-	-	0.43	0.41	0.46	0.23
3.15	$\dot{\varepsilon}_{1B}^H$	s^{-1}	0.2	0.254	0.33	0.3	0.42	0.6
3.16	ε_{1B}^H	-	0.84	0.82	0.78	0.91	0.93	0.88
3.17	t_B	s	4.5	3.6	2.0	2.3	1.9	1.46
3.18	$\dot{\varepsilon}_{2B}^H$	s^{-1}	0.19	0.23	0.38	0.4	0.5	0.6
3.19	t_n	s	-	-	6.2	5.5	6.6	6.1

Note: $D_0 = 100.5$ mm is the mean diameter and $\delta_0 = 0.7$ mm is the thickness of the annular drawing die.

4. DYNAMICS OF THE FILM-BLOWING PROCESS

Recently, we have proposed a new contactless pneumatic principle of nondestructive measurements of the longitudinal forces in the moving stretched film tubing [10],[11]. On this

principle, magnitudes of the longitudinal forces have been determined as functions of a differential pressure between two peripheral air-blast nozzles and one mean buried air-blast nozzle. These three nozzles are lying in the same plane and are evenly equidistant. While these three nozzles may tent to pull the stretched moving film tubing out of line, they are forced against the tubing by the jets with different intensity. Such, more or less, the stretched moving tubular film exhibit different resistances to air flows from these three nozzles. To sufficient accuracy the resistances to air flows from nozzles correlate with longitudinal forces in the more or less stretched tubular films.
The longitudinal tension force F_1 in the stretched film tubing can be calculated with the use of the differential pressure Δp between peripheral and mean nozzles in the following manner [10]

$$F_1 = 2A\Delta p\xi \quad (4.1)$$

The parameter ξ (N/mPa) in formula 4.1can be calculated as

$$\xi = 0.0322 + 108.65\delta_f \quad (4.2)$$

The longitudinal force F_{1p} caused by pressure p inside the tubular film can be calculated as

$$F_{1p} = 0.25\pi D_f^2 p \quad (4.3)$$

An external drawdown force F_{1ext} caused by a film takeup device can be determined by the following way

$$F_{1ext} = F_1 - F_{1p} - F_{1g} \quad (4.4)$$

where F_{1g} is a tension force stimulated by weight G_f (3.11) of the film bubble, N.
The stresses in the "1" direction (σ_{1f}) and in the "2" direction (σ_{2f}) on the freeze line of the film bubble can be determined along the following formulas, respectively

$$\sigma_{1f} = F_{1f}\left(2A\delta_f\right)^{-1} \quad (4.5)$$

$$\sigma_{2f} = 0.5pD_f\delta_f^{-1} \quad (4.6)$$

The stresses in the "1" direction (σ_{1n}) and in the "2" direction in the upper cross section of the bubble neck (σ_{2n}) can be calculated by proceeding as follows, respectively

$$\sigma_{1n} = F_1\left(\pi D_n\delta_n\right)^{-1} \quad (4.7)$$

$$\sigma_{2n} = 0.5pD_n\delta_n^{-1} \quad (4.8)$$

Dynamic parameters of the process are presented in Table 2.

5. HEAT ENERGETIC ASPECTS OF THE FILM-BLOWING PROCESS

The heat transfer intensity in the course of the polymer tubular film blow-molding can be characterized through an integrated coefficient only. In the case being considered there the cooling air temperature in the blower cooling ring 3 (see Fig. 1) is equal to the surrounding temperature (T_0).

The cooling ring is arranged in the way to provide exact control over speed of heat exchange by means of change of intensity of an exit of cooling air from the ring. Exact control over heat exchange process also is promoted by change of axial distance between the annual die and the cooling ring.

During t_f blowing formation the film bubble in weight G_f should be cooled from polymer melt temperature (T_m) on an exit from the die to temperature (T_f) polymer hardenings. Losses of thermal energy as a result of such cooling of a film sleeve can be calculated as follows:

$$Q = c_p G_p \left(T_m - T_f\right) g^{-1} \tag{5.1}$$

where c_p is the specific heat at constant pressure, J kg^{-1} K^{-1}.

Table 2: Dynamic parameters of the tubular film blow-molding

Numbers of Equation	Symbol	Dimension	Numbers of tubular film					
			1	2	3	4	5	6
	p	Pa	12	24	41	40	35	45
	Δp	Pa	30	60	105	100	120	150
4.2	ξ	m	0.045	0.045	0.042	0.041	0.039	0.036
4.1	F_1	N	0.98	1.94	3.0	3.2	3.68	4.1
4.3	F_{1p}	N	0.5	1.0	1.5	2.0	1.8	2.1
3.11	F_{1g}	N	0.23	0.25	0.48	0.58	0.58	0.45
4.4	F_{1ext}	N	0.24	0.69	1.0	0.71	1.32	1.55
4.5	σ_{1f}	kPa	11.3	22.4	49.0	51.0	76.7	154.1
4.6	σ_{2f}	kPa	11.5	22.9	49.2	62.0	74.7	156.0
4.7	σ_{1n}	kPa	-	-	22.6	20.5	30.2	64.0
4.8	σ_{2n}	kPa	0.95	1.9	4.9	8.2	4.5	11.2

These heat energy Q have been transferred from an external surface S_B with the mean temperature $0.5(T_m + T_f)$ to the cooling air with temperature T_0 in a time t_f (3.10)

$$Q = \alpha S_f t_f \left[0.5\left(T_m + T_f\right) - T_0\right], \tag{5.2}$$

where α is the averaged heat transfer coefficient on the film bubble area with height H_f, W m^{-2} K^{-1}.

An area of an external surface S_f of the film bubble can be approximately calculated by:

$$S_f = 0.5\pi H_f (D_f - D_0). \tag{5.3}$$

Rearrangement of Eq. 5.2 gives the averaged value of the heat transfer coefficient:

$$\alpha = Q\left\{S_f t_f \left[0.5\left(T_m + T_f\right) - T_0\right]\right\}^{-1}. \tag{5.4}$$

The computational heat energetic parameters of the various tubular film blow-molding processes are presented in the Table 3. As will be seen from Table 3, the averaged heat transfer coefficients only little vary from one film-blowing process to another. The reason is that the output of the cooling air from the blower cooling ring is held constant.

Let us suppose for arguments sake that the averaged heat transfer coefficients along the bubble neck area is held equal α . In this case the heat energy losses Q_n by cooling of the bubble neck can be writtenas:

$$Q_n = \alpha S_n t_n \left[0.5(T_m + T_n) - T_0 \right] \tag{5.5}$$

where S_n is the area of external surface of the bubble neck, m^2:

$$S_n = \pi D_n H_n \tag{5.6}$$

The bubble neck mass G_n can be calculated by follows:

$$G_n = q_v t_n \rho_m \tag{5.7}$$

Table 3: Heat energetic property of the polymer tubular film blow-molding

Numbers of Equation	Symbol	Dimension	Number of tubular film					
			1	2	3	4	5	6
	c_p	kJ/(kg·K)	2.5	2.5	2.5	2.5	2.5	2.5
	T_m	K	443	443	443	443	443	443
	T_f^*	K	388	388	388	388	388	388
	T_0	K	286	286	286	286	286	286
5.3	T_n	m^2	0.1	0.124	0.274	0.366	0.429	0.467
5.1; 5.2	Q	kJ	3.16	3.44	6.6	8.0	8.0	6.19
5.4	α	J/(m^2·s·K)	158	173	74	70	55	42.5
5.6	S_n	m^2	-	-	0.13	0.132	0.163	0.182
5.7	G_n	kg	-	-	0.04	0.046	0.051	0.039
5.5; 5.8	Q_n	kJ	-	-	3.13	3.34	3.06	2.41
5.9	T_n	K	-	-	412	414	412	418
5.10	K	K	55	55	24	26	24	30

Note: The film material: mixture of 70 % LDPE maker's label 15803-20 and 30 % HDPE maker's label 277.

As the first approximation, assumption is that the temperature T_n in the upper cross section of the bubble neck can be determinedas $T_f + 20K$. In this case we will get the heat energy Q_n

$$Q_n = c_p G_n (T_m - T_n) \tag{5.8}$$

Rearrangement of Eq. (5.8) gives the temperature T_n in the second approximation

$$T_n = T_m - Q_n \left(c_p G_n \right)^{-1} \tag{5.9}$$

The temperature reduction across the height $\left(H_f - H_n \right)$ of the film tubing inflation area can be determined in the second approximation as:

$$\Delta T_B = T_n - T_f \tag{5.10}$$

Thermal energy parameters of the process are presentedin Table 3.

6. RHEOLOGICAL ASPECTS OF THE POLYMER FILM TUBING BLOW-MOLDING

The Young's modulus of the stretched film bubble on the freeze line can be determined as:

$$E_{1e} = \sigma_{1f} \varepsilon_{1e}^{H^{-1}} \tag{6.1}$$

A hoop (tangent) modulus of elasticity of the film bubble on the freeze line can be calculated as:

$$E_{2e} = \sigma_{2f} \varepsilon_{2e}^{H^{-1}} \tag{6.2}$$

A longitudinal viscosity of the film bubble on the freeze line can be proceeding as:

$$\overline{\eta}_{1f} = \sigma_{1f} \dot{\varepsilon}_{1f}^{H^{-1}} \tag{6.3}$$

A hoop (tangent) viscosity of the film bubble on the freeze line can be determined as:

$$\overline{\eta}_{2f} = \sigma_{2f} \dot{\varepsilon}_{2f}^{H^{-1}} \tag{6.4}$$

A time of relaxation θ_{1f} in "1" and θ_{2f} in "2" directions on the freeze line of the film bubble can be defined, respectively, as [1],[4],[9]

$$\theta_{1f} = \overline{\eta}_{1f} E_{1e}^{-1} \tag{6.5}$$

$$\theta_{2f} = \overline{\eta}_{2f} E_{2e}^{-1} \tag{6.6}$$

The contributions of the hoop stresses on the upper cross sections of the bubble neck (in the beginning of the bubble inflation) to the hoop stresses on the freeze line can be defined as σ_{2n}/σ_{2f} .Then the contributions of elastic deformations (ε_{1e}^{H} , ε_{2e}^{H}) in the "1" and "2" directions to the total deformations (ε_1^H , ε_2^H) in the "1" and "2" directions of the tubular films can be determined, respectively, as:

$$\left.\begin{aligned} De_1 &= \varepsilon_{1e}^{H}\left(\varepsilon_1^H\right)^{-1}; \\ De_2 &= \varepsilon_{2e}^{H}\left(\varepsilon_2^H\right)^{-1}, \end{aligned}\right\} \tag{6.7}$$

where De_1 , De_2 are Deborah numbers for the "1" and "2" directions [9].
Size of a limit of cross-section elasticity σ_{2n} at which excess begins having inflated a polymeric sleeve, according to the results presented in table 2, can be approximately estimated as:

$$\sigma_{2n} = 0.1\sigma_{2f} \tag{6.8}$$

The mean longitudinal viscosity of polymer melt inside the bubble neck can be calculated in the following manner:

$$\bar{\eta}_{1n} = \sigma_{1n}\left(\dot{\varepsilon}_{1n}^{H}\right)^{-1} \qquad (6.9)$$

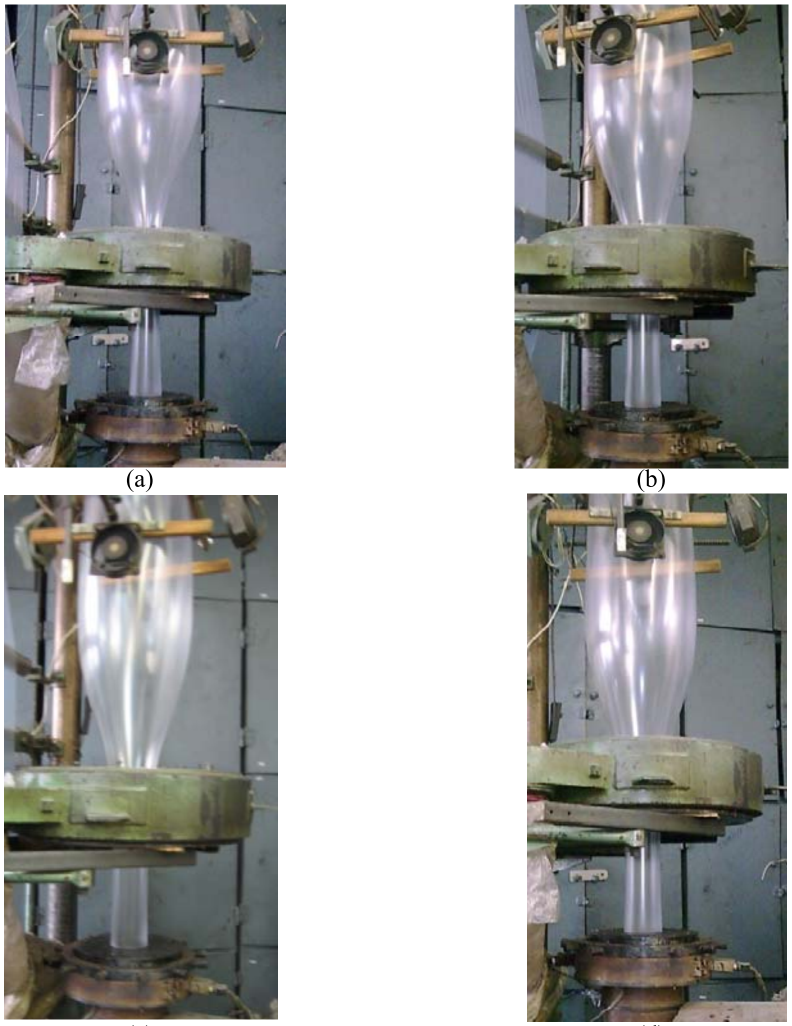
Rheological parameters of the process are presented in Table 4.

Table 4: Rheological property of the bubble polymer melts

Numbers of Equation	Symbol	Dimension	Number of tubular film					
			1	2	3	4	5	6
6.1	E_{1e}	kPa	9.4	16.2	28.8	26.8	47.9	85.6
6.2	E_{2e}	kPa	16.4	48.7	98.4	81.6	93.4	650
6.9	$\bar{\eta}_{1n}$	kPa·s	–	–	251	186	302	355
6.3	$\bar{\eta}_{1f}$	kPa·s	56.5	88.2	148.5	170	182.6	256.8
6.4	$\bar{\eta}_{2f}$	kPa·s	60.5	99.5	129.4	155	149.4	260
6.5	θ_{1f}	s	6	5.44	5.12	5.9	3.8	3
6.6	θ_{2f}	s	3.7	2.1	1.3	1.9	1.6	0.4
6.7	De_{1f}	–	1.2	1.5	1.3	1.5	1.0	0.85
6.7	De_{2f}	–	0.84	0.57	0.65	0.83	0.85	0.27
4.8; 4.6	σ_{2n}/σ_{2f}	–	0.08	0.08	0.1	0.13	0.06	0.07

7. EXPERIMENT

Experimental data (D_f , δ_f , H_f , v_f , D_0 , δ_0 , H_n , D_n , p , Δp , T_0 , T_f , λ_{1e} , λ_{2e} , λ_{3e}) have been obtained by measurements [10],[11] on tubular films production from polyethylene of high density on a technological line of manufacture of factory "Bolshevik" (Kiev, Ukraine). Other parameters have been defined by means of calculations.
The series of photographs demonstrating the tubular film blow-molding accompanied by the bubble necking were presented on Fig. 2.



(a) (b)

(c) (d)

Fig.2 – The series (a), (b), (c), (d) of photographs is demonstrating the bubble necking

The studied experimental and computational parameters are presented in Tables 1-4.

8. RESULTS AND DISCUSSION

When a polymer melt stream leaves an annular drawing die, the primary extrudate thickness increases. The ratio of the primary extrudate thickness to the annular die slit thickness is called the swell ratio, B_S. In the polymer melt flow as it leaves the die, more or less components of the stored elastic energy has been balanced by the elongation forces F_1 acting on the stretched film tubing [12].

The greater is the tension force F_1 on the bubble neck, the less it is effected die swelling, the less it is the swell ratio, B_s, and the total draw ratio λ_1. The smaller is the tension force F_1 in the bubble neck, the greater is the stored elastic energy dissipation in the extrudate, the greater is the swell ratio, B_s, as the result of the post-extrusion swelling [9], and the greater is the total draw ratio λ_1 in the bubble neck. By this means, the nonsensical superiority of the longitudinal elastic deformation ε_{1e}^H over the total deformation ε_1^H is connected with an ignoring the swelling effect of the polymer extrudate during flow from a slit of the annular drawing die [12]. Examples are found in correlation made between film No 1 ($F_1 = 0.98N$) and film No 6 ($F_1 = 4.1N$). Such examples provide insight into a reduction of ratio $\varepsilon_{1e}^H / \varepsilon_1^H$ from 1.2 to 0.85 (see Table 1). The reduction has been generated by the elastic energy balance in the extrudate swelling area under an action of the greater longitudinal forces F_1.

Polymer melts on the different steps, by which a blow-molding proceeds can be treated as solid or liquid depending on the Deborah number, which is the ratio between an inherent time-scale (θ_{1f}, θ_{2f}) and a characteristic time of loading (t_f, t_B). The Deborah numbers De_{1f} for longitudinal (index "1") tension on the freeze (index " f ") line and the Deborah numbers De_{2f} for cross traverse (2) tension on the freeze (f) line for Nos 1–6 films have been summarized in Table 4. The averaged Deborah number ($De_1 = 1.2$) for the "1" direction exceed the averaged Deborah number ($De_2 = 0.67$) for the " 2 " direction. This is in general agreement with the existence of the elastic anisotropy of the tubular films.

The magnitudes of the external draw down force F_{1ext} are presented in Table 2 for various modes of operation. As will be seen from Table 2, it can be said with confidence that the external draw down force F_{1ext} make up the principal components of the total longitudinal tension force in the stretched film tubing. Ignoring this force in the published works [2],[3],[5],[6] may introduce large errors. One can say with a fair degree of confidence that transition from the bubble necking to the tubular film inflation starts when the neck upper cross section parameters may be as much as T_n, δ_n, σ_{2n} (see Tables 1-4), where

$$\left.\begin{aligned} T_n &= T_f + 26(K); \\ \delta_n &= 6\delta_f; \\ \sigma_{2n} &= 0.1\sigma_{2f}. \end{aligned}\right\} \quad (8.1)$$

With the availability of these parameters in the upper cross section of the bubble neck it will be possible the transition to the equibi-axial extension in the tubular film inflation area.

9. CONCLUSIONS

As a result of the performed work it is possible to draw following conclusions.

1. Temperature, kinematic and dynamic conditions of transition from neck formation to uniform biaxialstretching in a film-blowing zone are established.
2. The method of the approached estimation of kinematic, dynamic and power parameters of

tubular polymer films formation process in the conditions of high-efficiency extrusion of polymers melts is developed.

3. Representation about interrelation between kinematic, dynamic, rheological and heat power main parameters is received at extrusion of tubular polymer films with formation of a neck in the conditions of high-efficiency extrusion of polymers melts.

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Nomenclature

A	is width of tubular film in packed up form, m
B , B_n	are blow up ratio of the film tubing and the neck, respectively
B_s	is swell ratio
b_f , b_t	are width of the film specimen and of the heat treated specimen, respectively, m
c_p	is specific heat at constant pressure, kJ/(kg·K)
D_f , D_n , D_0	are diameters ofcooledfilm tubing, neck and the annular drawing die, respectively, m
De_1 , De_2	are averaged Deborah number in the "1" and "2" directions, respectively
E_{1e} , E_{2e}	are modulus of elasticity in the "1" and "2" directions, respectively, kPa
F_1 , F_{1g} , F_{1ext}	are tension force in the "1" direction total, stimulated by weight an external act, respectively, N
G_f , G_n	are total weight of the film bubble and the neck weight, respectively, N
g	is free fall acceleration, m/s^2
H_f , H_n	are the freeze line height and the bubble neck length, respectively, m
l_f , l_t	are length of the film specimen and of the heat treated specimen, respectively, m
Q , Q_n	are heat energy losses by film bubble and by neck, respectively, J
q_v	is volumetric output, m^3/s
S_B , S_f , S_n	are external surface of the film bubble (index B) in the inflation area, total (index f), in the necking area (index n) , respectively, m^2
T_f , T_m , T_0 , T_n	are temperature on the freeze line (f), of polymer melt (m), of cooling air(0), in upper cross section of neck (n), respectively, K
ΔT_B	is the drop in temperature across the height of the film tubing inflation area, K
t_B , t_f , t_n	are times of forming (B) the tubing inflation area, (f) the film bubble, (n) the neck, respectively, s
v_f , v_n , v_0	are the take up speed (f),speed in upper cross section of neck (n), (0) the mean polymer melt outlet velocity from drawing die, respectively, m/s
α	is average heat transfer coefficient, J/(m^{2}sK)
δ_f , δ_n , δ_0	are thickness of bubble on freeze (f) line, in upper cross section of neck (n), (0) of annular drawing die, respectively, m
ε_1^H , ε_2^H , ε_{1B}^H	are total Hencky's strain in the "1", "2" directions and (B) longitudinal strain of bubble on the inflation area, respectively
ε_{1e}^H , ε_{2e}^H , ε_{3e}^H	are recoverable Hencky's rate-of-strain in the "1", "2"and "3"directions, respectively, s^{-1}
$\dot{\varepsilon}_1^H$, $\dot{\varepsilon}_2^H$	are total Hencky's rate-of-strain in the "1", "2" directions, respectively, s^{-1}
$\dot{\varepsilon}_{1B}^H$, $\dot{\varepsilon}_{2B}^H$	are Hencky's rate-of-strain of bubble on the inflation area in the "1", "2" directions, respectively, s^{-1}
$\dot{\varepsilon}_{1n}^H$	is Hencky's rate-of-strain in upper cross section of neck in the "1" direction, s^{-1}
$\bar{\eta}_{1f}$, $\bar{\eta}_{2f}$, $\bar{\eta}_{1n}$	are longitudinal viscosity, tangent viscosity on the freeze line and longitudinal viscosity of neck, respectively, Pa·s

θ_{1f} , θ_{2f} are times of relaxation in the "1", "2" direction on the freeze line, respectively, s

λ_1 , λ_2 are total draw ratio in the "1", "2" directions, respectively

ξ is parameter of longitudinal tension, m

π is 3.14159

ρ_t , ρ_m are density of the cooled and melted polymer, respectively, kg/m^3

σ_{1f} , σ_{2f} are stresses in the "1", "2" directions on the freeze line, respectively, Pa

σ_{1n} , σ_{2n} are stresses in the "1", "2" directions in the upper cross section of neck, respectively, Pa

FORMIRANJE VRATA KOD PROIZVODNJE CEVASTOG POLIMERNOG PROIZVODA DUVANJEM

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REZIME

Povećanjem količine ekstudiranog polimera povećava se cevasta oblast filma sa pojavom stvaranja mehura. To dovodi do akumulacije velikih napona u dvoosno orijentisanom termo-skupljajućem cevastom filmu polimera. Formiranjem mehura u vratu (suženju) je karakterizovano kinematičkim, dinamičkim, reološkim i termalno energetskim parametrima koji utiču jedan na drugi. Na osnovu teorijskih i eksperimentalnih studija ustanovljena je veza između ovih parametara što omogućava da se utiče na osobine filma koji se proizvodi, naročito na njegovu izdržljivost. Takođe je upoređen mehanizam prelaza cevastog film bez stvaranja vrata pri malim brzinama sa onim koji se pojavljuje kod istih procesa ekstuzije u kojima se formira vrat sa velikim brzinama.

Ključne reči: ***e****kstruzija, cevasti polimerni film, vrat, parametri*