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8 July, 1996

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Dear Participant,

I am pleased to inform you that your paper has been included in the Final Program of the Congress as follows:

Paper No.: P7.114 Ref. No.: 0270
Authors: Uliev, L. M. (asterisk denotes the author delivering the paper)
Affiliation: State Polytech. Univ., Kharkov, Ukraine
Title: Non-isothermal flow of high-viscosity melts of thermoplastic polymers in conic-cylindrical dies

Presentation: poster, Thursday

I am looking forward to meeting you in Prague.

Sincerely yours,

Ivan Wichterle
Scientific Committee

NON-ISOTHERMAL FLOW OF HIGH-VISCOSITY MELTS OF THE THERMOPLASTIC POLYMERS IN CONIC-CYLINDRICAL DIES

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This work investigates the flow of polymers in the conic-cylindrical dies for a distance-varying, along the flow, heat exchange with the environment. It shows the possibility of control of temperature field, velocity field and pressure field in the channel with the help of variation of intensity of heat exchange of melt with the environment. It allows to choose the optimum structural and technological parameters of the processes of production and processing of polymers.

For continuous synthesis of thermoplastic polyurethanes (TPU) and in further receipt of semi-manufactured goods in the shape of pellets under granulation is used where the melt of polymer is pressed through circular conic-cylindrical channels, and received strands are cut into the pellets which are taken away by running water.

Flow and heat transfer of melt thermoplastic in circular cofusers were investigated in [1]. The non-isothermal flow for cylindrical part of the dies was investigated in [2-3]. They show that the knowledge of the temperature and velocity distributions demands for selection of optimum technological and structural parameters of granulator.

Non-isothermal flow of the melt polymers with temperature-dependent viscosity in the conic-cylindrical dies was considered in [4] for constant of wall temperature. The numbers of Nahme-Griffith were $\sim 10^{-3}$ here, i.e. dissipation effects had no influence on the hydrodynamics parameters of the stream.

The dissipation effects predominate with flow TPU in the extrusion heads [1-3]. It can lead to unsteady work of granulator [3]. The design of die plate for steady form was proposed in [6]. Each channel of the die plate here is surrounded by the channel with heat carrier which is placed between thermal insulation gaskets (Figure 1.).

The melts of several kinds of TPU within the alteration of parameters of processing are alike Newtonian liquids with the Arrenius dependence [6], $\mu(T) = \mu_0 \exp\left[E/R\left(1/T - 1/T_0\right)\right]$, where $\mu_0 \approx 10^3 \, \mathrm{Pa \cdot s}$, $E \approx \left(10^5 ... 3 \times 10^5\right) \mathrm{J/mole}$, $T_0 = 463°$ K. The big values of viscosity and the low of thermal conductivity allow to simulate the flow of melt by the equation of creeping flow and in heat transfer equation to take into account dissipation, longitudinal and cross convection but to neglect longitudinal conductivity [1-3].

To solve this conjugated problem (Gn>>1) the region of flow is separated into N concentric conical layers in confuser and cylindrical in cylinder. We assume that viscosity in cross-section of each layer is constant and equal to one taking for average temperature on section of this layer. Owing to this method the set of equations of motion and heat transfer is reduced to the set 2N ordinary differential equations for the mean temperatures and pressures in layers of confuser and the set N+1 of ordinary differential equations in cylinder, and the set of analytical expressions for component velocities of liquid.

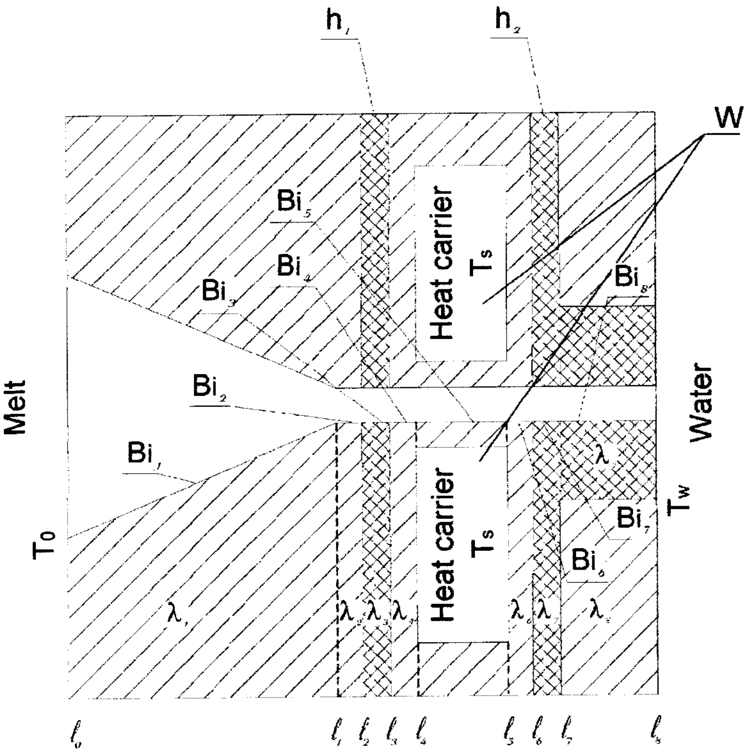

Figure 1. The diagram of die channel. T_0- the temperature of melt on the entry of the channel; T_w- the temperature of water carrying out the pellets; T_s- the temperature of the heat carrier; h_1, h_2- the thermal insulation gaskets; W- the channel with heat carrier. The coefficients of thermal conductivity are $\lambda_1 = \lambda_2 = \lambda_4 = \lambda_6 = \lambda_8 = 16$ W/m K, $\lambda_3 = \lambda_7 = 0.2$ W/m K. Biot's numbers are $Bi_1 = 3.93$, $Bi_2 = Bi_4 = Bi_5 = Bi_6 = 4.073$, $Bi_3 = 0.3$, $Bi_7 = 0.334$, $Bi_8 = 0.42$. The co-ordinates of the wall layers are $l_0 = 0$, $l_1 = 4.6 \cdot 10^{-2}$m, $l_2 = 4.9 \cdot 10^{-2}$m, $l_3 = 5.4 \cdot 10^{-2}$m, $l_4 = 5.9 \cdot 10^{-2}$m, $l_5 = 7.4 \cdot 10^{-2}$m, $l_6 = 7.9 \cdot 10^{-2}$m, $l_7 = 9.4 \cdot 10^{-2}$m, $l_8 = 0.1$m.

Boundary conditions of the third kind are chosen here, and, as far as each die is surrounded by other ones, so Θ_a is the temperature of the die body depended from longitudinal co-ordinate, because the temperature of die plate changes from the temperature of the melt in distribution system to the temperature of cool water from the side of the knives with under granulation.

In [2-4] we see the possibility of the control by stream of melt with the help of changing of intensity of heat exchange on boundary. Therefore, here we will consider the dies surrounded by the special channels with heat carrier. These channels are disposed between thermal insulation gaskets (Figure 1). Furthermore, if the channel W is absent then the thermal insulation gasket is absent too, and then from co-ordinate l_3 to l_4 $\Theta_a = \Theta_s$ (Figure 1).

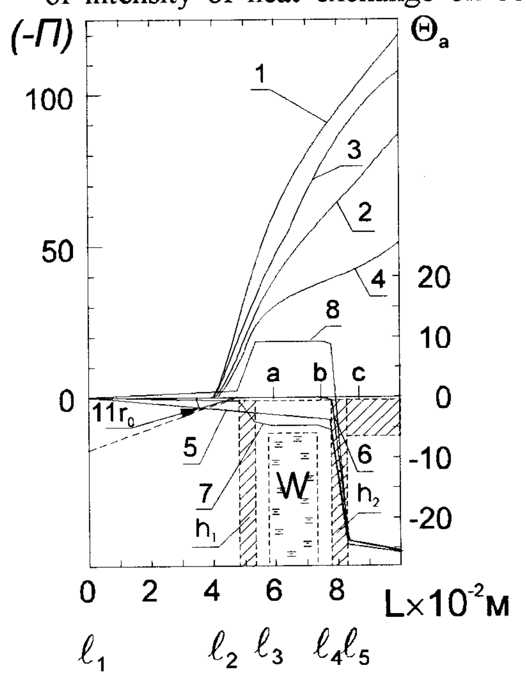

Figure 2. Dimensionless pressure distributions (1,2,3,4) along the channel of die: dimensionless temperature distributions (5,6,7,8) in wall of die; 1,5 -the die without channel W; 2,6- for $\Theta_S = 0$; 3,7- for $\Theta_S = -4.96$; 4,8 - $\Theta_S = 9.02$.

For studying the peculiarities of the flow and heat exchange let us describe the problem with parameters Pe = 1591.6, Gn = 21.2, $\beta = 1.44 \cdot 10^{-2}$, $\Delta T_{rheol} = 6.65$, $R_0 =$

$5.33 \cdot 10^{-2}$m, $\Lambda = 0.0857$, $r_0 = 1.5 \cdot 10^{-3}$ m, $2\theta_0 = 38°$ and analyse four variants of heat exchange: 1) the flow in the die without channel W; 2) the flow with $\Theta_s=0$; 3) $\Theta_s = -4.96$; 4) $\Theta_s = 9.02$.

In the beginning of the channel velocity of liquid is small and for all cases the dissipation there is not significant. Therefore with $\Theta_s=0$; $\Theta_s= -4.96$; and $\Theta_s=9.02$ the temperature Θ_a is close to Θ_0, owing to it the distribution of temperature and velocity remains almost without change, the pressure decreases very slowly too (Figure 2). For $\Theta_s=9.02$ the melt in confuser is slightly heated (negative heat flux on wall (Figure 3)), that provides only insignificant decreasing of |gradP|.

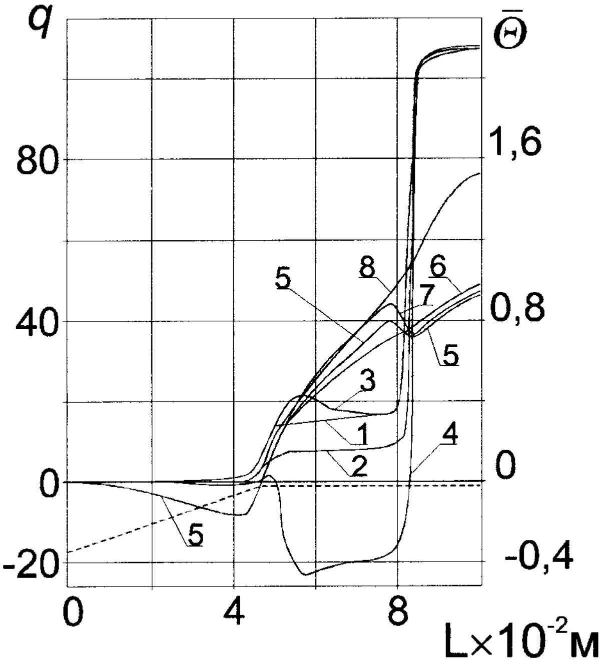

Figure 3. Dimensionless heat flux distributions (1,2,3,4) on boundary and of mean temperature distributions (5,6,7,8) along the channel. 1,5 -die without W; 2,6 - for $\Theta_S = 0$; 3,7- for $\Theta_S = -4.96$; 4,8 - $\Theta_S = 9.02$.

When the channel W is absent, Θ_a decreases along the confuser strongly (Figure 2), and liquid is cooled on periphery of the channel (q>0 (Figure 3)), and the profile of velocity $u=v_{co}\kappa^2$ stretches out (Figure 4). In this case the modulus of gradient of pressure is larger than in other cases owing to increasing of viscosity on the periphery of flow. With $\Theta_s = -4.96$ we see analogous effects, but they are less expressed because of presence of thermal insulation gasket h_1.

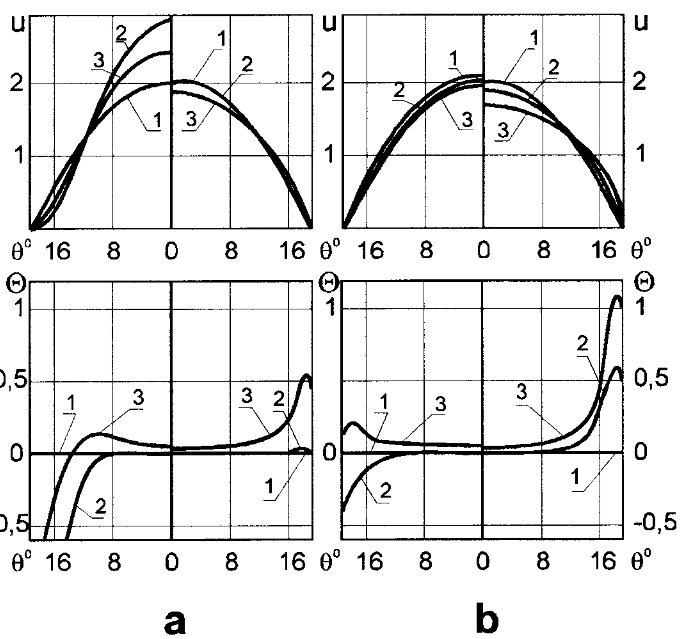

Figure 4. These are distribution of dimensionless: the radial velocity $u(\tau)$- up pictures and temperature - down. a) left half is for die without W, right -with W and $\Theta_S = 0$; b) left half for $\Theta_S = -4.96$; right- $\Theta_S = 9.02$. 1-on enter in confuser, $R = 35.5\ r_0$; 2- for $R = 11r_0$; 3- on exit from confuser, $R = 3.05r_0$.

Close by exit from confuser the velocity of liquid and accordingly the dissipation of energy increase significantly, the gradient of pressure increases, too (Figure 2). The temperature of liquid raises on periphery of the channel (Figure 4). The temperature increases even in a die without the channel W, but close by axis and not by the wall where liquid is cooled (Figure 4). In the cylindrical part of channel $|d\Pi/d\chi|$ is sharply increases in all the cases, but in consequence of various conditions of heat exchange its conduct is different.

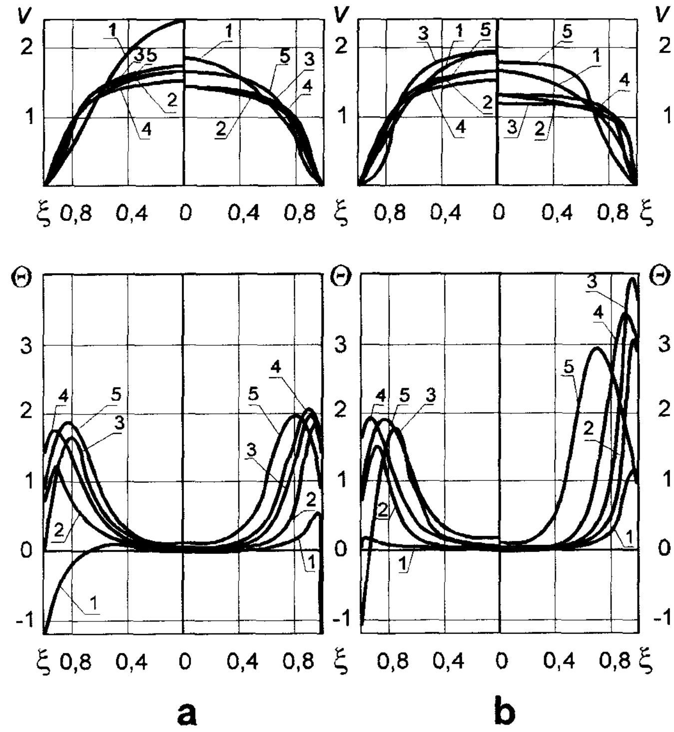

Figure 5. The distributions of dimensionless: of the longitudinal component velocity in cylinder in up and temperature in down. a) left half is for die without W,right -with W and $\Theta_S = 0$; b) left half- $\Theta_S = -4.96$; right- $\Theta_S = 9.02$. 1- for enter; 2- for distance $7.2r_0$ from enter (section a on Figure2); 3- 18 r_0 (section b); 4- 25.2 r_0 (section c); 5 - on exit.

The pressure drop is the biggest for flow in a die without the channel W because cooled on the periphery liquid enters the cylindrical channel. It carries out to the bigger dissipation and pressure drop. The heat flux on boundary is the biggest in this case as difference $|\overline{\Theta}_N - \Theta_a|$ and dissipation of energy is the biggest here. However with $\Theta_S = -4.96$ heat flux becomes bigger in the region gasket h_1 as in this case Θ_a is smaller than in case 1. The profile of velocity slightly stretches out here, remaining its plug flow form with the bend by the wall (Figure 4), but for small Re it does not carry out to instability. The distributions of pressure in cases 1) and 3) are similar.

For $\Theta_S = 0$ and $\Theta_S = 9.02$ the liquid enters in the cylinder with more developed heat layer and more flat profile of velocity (Figures 4,5). For $\Theta_S = 0$, $\Theta_a = 0$ practically to gasket h_1, and the change of temperature of stream occurs on this interval only owing to dissipation of energy. Because Θ_a is higher than in early considered cases, profile of velocity here is more flat (Figure 5). In the case $\Theta_S = 9.02$ liquid is heated with flow in confuser from ambient, q is negative (Figure 3). In the cylinder the temperature of liquid on periphery becomes higher Θ_a owing to dissipation, and heat flux changes its direction and it reminds positive to gasket h_1 (Figure 3), within which Θ_a increases, q here again changes sign and liquid is heated from heat carrier (Figures 3,5). In region between gaskets $|d\Pi/d\chi|$ decreases because of the decreasing of viscosity on periphery, in consequence of it profile of velocity is more filled here.

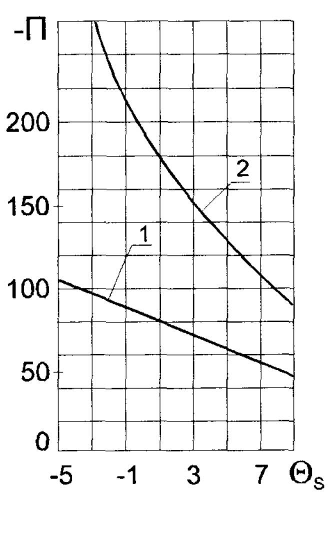

Figure 6. The dependence dimensionless pressure drop on die from Θ_S; 1 -for parameters Pe = 1591.6, Gn = 21.2; 2- Pe = 530.5, Gn = 2.35.

In region of the second gasket h_2, Θ_a significantly decreases (Figure 2), and in all considered cases liquid begins intensively cool on the periphery, here heat flux to ambient medium quickly grows (with $\Theta_S = 9.02$ it changes sign again), reaching behind gasket h_2 value is equivalent for all cases (Figure 3) as here Θ_a almost does not change across the plate for all variants. The profile of velocity here stretches out, and, it is obvious that to remain more filled profile of velocity on exit from die, which ensures receipt of qualitative product [3], it is necessary to line exit part of channel by more capacity of heat insulation.

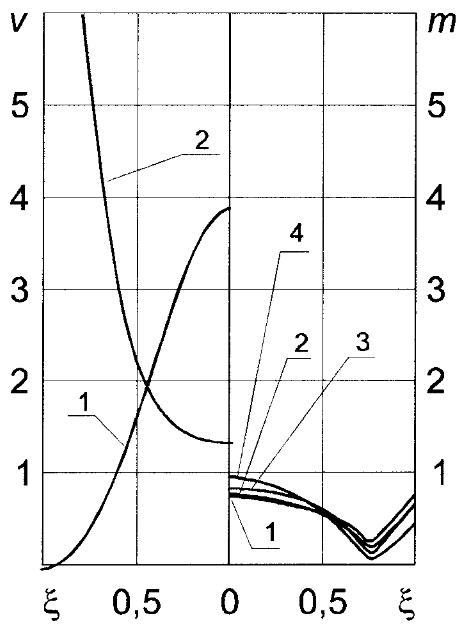

Figure 7. Left half: distributions of the longitudinal velocity v- 1, and dimensionless viscosity - 2 on radius on exit from die without W and gaskets h. Right: dimensionless viscosity distributions: 1 without W; 2 - for $\Theta_S = 0$; 3- for $\Theta_S = -4.96$; 4- $\Theta_S = 9.02$.

It is shown in [3] heat regime of flow of thermoplastic polymers is determined on the whole by number Gn. The dependence Π(Gn) turns out to be so significant that it is impossible to granulate TPU of various recipes, using one die plate. But if the channel W is present we can change the pressure drop on die plate changing Θ_S. On figure 6 it is shown the dependence Π(Gn) for flow of melt polymer with different flowrates. Dependence Π(Gn) is stronger for small velocity (smaller Pe), so influence of dissipation here is small, and liquid has bigger residence in region of intensive heat exchange and it can be heated or cooled more evenly. Therefore here the influence of dependence μ(T) is stronger than for bigger velocity. For big velocity the flow has the high temperature character [4], when small viscosity layer is formed on periphery in consequence of dissipation and plug flow with small gradient pressure is formed on bigger of the channel part. Therefore pressure drop for bigger Pe is smaller (Figure 6), and dependence $\Pi(\Theta_S)$ is weaker.

We can choose the pressure drop necessary for technological region of polymer processing for synthesis of various sort of TPU with the help of one die plate.

It is necessary to note that if the channel and heat insulation gaskets are absent in construction of die plate the profile of velocity will be stretched out on exit of die, and the viscosity will strongly increase to periphery (Figure 7). The breach of regime of polymer processing can take place for these conditions.

NOMENCLATURE

c- specific heat [J kg^{-1} K^{-1}], E- energy of activation of viscous flow [J mol^{-1}], P, P_0- pressure, current and inlet [N m^{-2}], r, r_0- radius current and of cylinder [m], R_0,R_1,R- radial spherical co-ordinate, forming of confuser and its truncated part, R^*- universal gas constant [J mol^{-1} K^{-1}]; T, T_0- temperature of melt, current and inlet [K], V_0- mean velocity in cylinder [m s^{-1}], $v_{co} = V_R/V_0$, $v = V_z/V_0$, z - longitudinal co-ordinate [m], $\beta = R^*T_0/E$; $\Lambda = R_1/R_0$, $\Theta = (T-T_0)/\beta T_0$; θ,θ_0- angular spherical co-ordinate and angle opening of confuser; $\kappa = R/r_0$; $\xi = r/r_0$; $\chi = z/r_0$; $\Pi = (P-P_0)r_0/\mu_0 V_0$; N_{Bi}- Biot number, $Gn = \frac{\mu_0 V_0^2}{\lambda \beta T_0}$ - Nahme-Griffith number, Pe- Peclet number, $Re = \frac{\rho V_0 r_0}{\mu_0}$ - Reynolds number, α- thermal diffusivity of melt [m^2 s^{-1}], λ- thermal conductivity of melt [J m^{-1} $s^{-1}K^{-1}$], μ- dynamic viscosity of melt [kg m^{-1} s^{-1}], ρ- density [kg m^{-3}].

Subscripts: a- relating to ambient, s- to heat carrier.

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