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В четвертой части представлены работы, отражающие актуальные вопросы использования ЭВМ для решения задач разработки и совершенствования химических технологий.

Для научных работников, специалистов, преподавателей, аспирантов, студентов высших учебных заведений соответствующих специальностей.

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FEATURES OF CONFUSER NON-ISOTHERMAL PRESSURE DROP-FLOWRATE CHARACTERISTIC.

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В работе моделируется неизотермическое течение высоковязких расплавов полимеров в конических фильерах при больших числах Нема-Гриффита. Исследована напорно- расходная характеристика конфузоров. Обнаружено, что в конфузорах с малыми углами раскрытия напорно-расходная характеристика немонотонна.

Many processes of production and processing of polymers are connected with their flow through circular confuser. But melts of some thermoplastic polymers within the alteration of processing parameters are alike high-viscosity Newtonian liquids with Arrenius dependence of viscosity on temperature $\mu(T)=\mu_0\exp[E/R(1/T-1/T_0)]$, where $\mu_0\approx10^3\,Pa\cdot s$, $E\approx(10^5...2.7\times10^5)J/mole$, T_0 = 463° K [1], their flow takes place in condition of the big gradients of the temperature and viscosity in consequence of sharp viscosity - temperature dependence. Therefore it is necessary with investigation of such fluid flows to take into account both dissipation and heat exchange at boundary.

For flowrate, presenting practical interest $Q=10^{-5}...10^{-7}$ m^3s^{-1}, physical property, $\rho\sim1200$ kg m^{-3}, $a\sim10^{-7}m^2\,s^{-1}$ and $R_0\sim(1...6)\cdot10^{-2}$ m, number $Re<<10^{-2}$, $Pe\sim10^5$, and then length, on which mechanical relaxations take place is smaller on many order than interval of thermal relaxation.

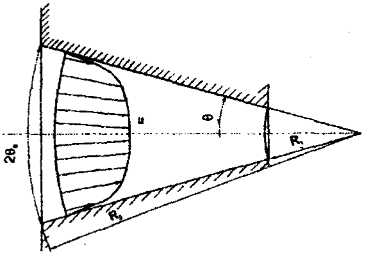

Figure 1. Diagram of confuser channel. R_0, R_1- forming of confuser and its truncated part; $2\theta_0$ - angle of confuser opening.

It was shown in [2] that with slow flow in confuser with an angle opening $2\theta_0$< 120° (Fig. 1) we can neglect angle component of the velocity V_θ in motion equation written in spherical co-ordinates in comparison with V_R. Taking all these into account we can simplify the set of hydrodynamic and heat transfer equations for steady axial symmetrical flow in the confuser [3].

$$\frac{\partial P}{\partial R}=\frac{\partial\sigma_{RR}}{\partial R}+\frac{1}{R}\frac{\partial\sigma_{\theta R}}{\partial\theta}+\frac{2\sigma_{RR}-\sigma_{\varphi\varphi}-\sigma_{\theta\theta}+\sigma_{\theta R}ctg(\theta)}{R}, \quad (1)$$

$$\frac{1}{R}\frac{\partial P}{\partial\theta}=\frac{\partial\sigma_{RR}}{\partial R}+\frac{1}{R}\frac{\partial\sigma_{\theta\theta}}{\partial\theta}+\frac{(\sigma_{\theta\theta}-\sigma_{\varphi\varphi})ctg(\theta)+3\sigma_{\theta R}}{R}, \quad (2)$$

$$\frac{\partial V_R}{\partial R}+\frac{1}{R}\frac{\partial V_\theta}{\partial\theta}+\frac{2V_R}{R}+\frac{V_\theta ctg(\theta)}{R}=0, \quad (3)$$

$$V_R \frac{\partial T}{\partial R} + \frac{V_\theta}{R}\frac{\partial T}{\partial \theta} = a\left[\frac{1}{R^2}\frac{\partial}{\partial R}\left(R^2 \frac{\partial T}{\partial R}\right) + \frac{1}{R^2 \sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial T}{\partial \theta}\right)\right] + \Phi, \qquad (4)$$

where the components of stress tensor are $\sigma_{RR} = 2\mu \frac{\partial V_R}{\partial R}$; $\sigma_{R\theta} = \mu \frac{1}{R}\frac{\partial V_R}{\partial \theta}$; $\sigma_{\varphi\varphi} = 2\mu \frac{V_R}{R}$; $\sigma_{\theta\theta} = 2\mu \frac{V_R}{R}$,and dissipation function is $\Phi=\sigma_{lk}\varepsilon_{lk}$, where $\varepsilon_{lk}=\sigma_{lk}/2\mu$- rate of strain tensor.

The boundary conditions are:

$$\frac{\partial V_R}{\partial \theta} = 0, \frac{\partial T}{\partial \theta} = 0, V_\theta = 0, \qquad \theta = 0, \qquad (5)$$

$$V_R = 0, \frac{\lambda}{R}\frac{\partial T}{\partial \theta} = -K(T - T_a), \qquad \theta = \theta_0, \qquad (6)$$

$$T = T_0, \qquad 0 \le \theta < \theta_0, \qquad (7)$$

$$P(\theta) = P_0, \qquad R = R_0,\ \theta = \theta_0, \qquad (8)$$

and condition of constant of flow rate will be written $Q = 2\pi R^2 \int_0^{\theta_0} V_R \sin\theta d\theta$.

To solve this conjugated problem (Gn>1) the region of flow is separated into N concentric conical layers in confuser and it is assumed that viscosity over cross-section of each layer is constant and equal to one taking for average temperature over cross- 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 analytical expressions for components of velocity, dissipation function and heat transfer coefficients between layers:

$$\frac{d\overline{\Theta}_i}{d\xi} = \frac{1}{\xi(\tau_i - \tau_{i-1})\overline{u}_i}\left\{\sqrt{1-\tau_{i-1}^2}(\omega_{i-1} + St_{i-1})(\overline{\Theta}_i - \overline{\Theta}_{i-1}) - \sqrt{1-\tau_i^2}(\omega_i - St_i)(\overline{\Theta}_i - \overline{\Theta}_{i+1})\right\} + \frac{Gn}{Pe}\frac{\overline{\Phi}_i}{\overline{u}_i}, \qquad (9)$$

$$\frac{d\overline{\Pi}_i}{d\xi} = \frac{3m_N k_N}{P_2(\tau_N)\xi^4}\left[1 - (\tau_i^2 + \tau_i\tau_{i+1} + \tau_{i+1}^2)\right], \qquad (10)$$

$$u_i(\tau) = v_i \xi^2;\ u_i(\tau) = k_N\left\{\frac{m_N}{P_2(\tau_N)}\left[\frac{P_2(\tau)}{m_i} + S_i\right] - 1\right\}, \tau_i \le \tau \le \tau_{i-1} \qquad (11)$$

$$k_N = \frac{\Lambda(\tau_N - 1)}{\sum_{K=1}^{N}\left\{\frac{m_N\left[(\tau_K^3 - \tau_K) - (\tau_{K-1}^3 - \tau_{K-1})\right]}{2m_N P_2(\tau_N)} - \left[\frac{m_N}{P_2(\tau_N)}S_K - 1\right](\tau_K - \tau_{K-1})\right\}},$$

$$S_i = \sum_{K=1}^{N-1}\left(\frac{1}{m_{K+1}} - \frac{1}{m_K}\right)P_2(\tau_K),\ \omega_i = \frac{1}{\xi\sqrt{1-\tau_i^2}}\sum_{j=1}^{i}(\tau_j - \tau_{j-1})\frac{d\overline{u}_j}{d\xi},\ \overline{\Theta}_{N+1} = \Theta_a,$$

$$P_2(\tau)=\frac{1}{2}\left(3\tau^2-1\right),\ \bar{u}_i=k_N\left\{\frac{m_N\left(\tau_i^2-\tau_i\tau_{i-1}-\tau_{i+1}^2+1\right)}{2P_2(\tau_N)m_i}+\left[\frac{m_N}{P_2(\tau_N)}S_i-1\right]\right\},$$

$$St_i=\frac{Nu_i}{Pe},\ Nu_i=\frac{2}{\xi\sqrt{1-\tau_i^2}}\left\{\frac{1}{\tau_i-\tau_{i-1}}\left[\left(1+\tau_{i-1}\right)\ln\frac{1+\tau_i}{1+\tau_{i-1}}+\left(1-\tau_{i-1}\right)\ln\frac{1-\tau_i}{1-\tau_{i-1}}\right]-\right.$$

$$\left.-\frac{1}{\tau_{i+1}-\tau_i}\left[\left(1+\tau_{i-1}\right)\ln\frac{1+\tau_{i+1}}{1+\tau_i}+\left(1-\tau_{i+1}\right)\ln\frac{1-\tau_{i+1}}{1-\tau_i}\right]\right\}^{-1},$$

$$\overline{\Phi}_i=\frac{9k_N^2m_N^2}{P_2^2(\tau_N)m_i\xi^6}\overline{\left[\left(1-\tau^2\right)\tau^2\right]}+\frac{2m_i}{\xi^4}\left\{\frac{6}{\xi^2}\overline{u_i(\tau)}-\frac{4}{\xi}\overline{u_i(\tau)\frac{du_i(\tau)}{d\xi}}+\overline{\left[\frac{du_i(\tau)}{d\xi}\right]^2}\right\},$$

where $\tau=\cos\theta,\ \xi=\frac{R}{R_0},\ \Pi=\frac{(P-P_0)R_0}{\mu_0V_0},\ v=\frac{V_R}{V_0},\ \omega=\frac{V_\theta}{V_0},\beta=\frac{R^*T_0}{E},\ \Theta=\frac{(T-T_0)}{\Delta T_{rheol}},$

$$\Lambda=\frac{R_1}{R_0},V_0=\frac{Q}{2\pi(1-\cos\theta_0)R_0R_1},\ m=\frac{\mu(T)}{\mu(T_0)}=\exp\left(-\frac{\Theta}{1+\beta\Theta}\right),\ Bi=\frac{KR_0}{\lambda},Gn=\frac{\mu(T_0)V_0^2}{\lambda\Delta T_{rheol}},$$

$$\Delta T_{rheol}=\left|\mu(T)\Big/\left(\frac{\partial\mu}{\partial T}\right)\right|_{T=T_0}=\frac{R^*T_0^2}{E}=\beta T_0,\ Pe=\frac{V_0R_0}{a}.$$

The derivatives are calculated with the help of expression $\frac{dm_i}{d\xi}=-\frac{m_i}{1+\beta\overline{\Theta}_i}\frac{d\overline{\Theta}_i}{d\xi}$.

The distributions of velocity, temperature and pressure are obtained with integration of equations (9,10) as function of problem parameters. Some distributions are represented on Figure 2 for parameters $Pe=2.02\cdot10^4$, $Gn=1.654$, $Bi=169.8$, $\beta=1.44\cdot10^{-2}$, $\Delta T_{rheol}=6.65$, $R_0=5.33\cdot10^{-2}$m, $\Lambda=0.0857$, $2\theta_0=38°$ and temperatures of ambient medium 1) $\Theta_a=0$; 2) $\Theta_a=1.5$; 3) $\Theta_a=-1.5$.

The liquid flow along confuser is accompanied with increase of mean velocity over cross-section of the channel. It leads to the increase of shear rate, especially in periphery region, and, as a consequence, the energy dissipation is increased at the channel wall (Fig. 2f)., owing to this the temperature is increased there and the viscosity is decreased (Fig.2). Profile of the velocity is become more and more filled, i.e. the shear rate on the periphery is increased more, and that carries out to localization of heat generation (Fig. 2.f).

The effects connected with the dissipation of mechanical energy become dominated on some distance from entrance. It carries out to appearance of small viscosity high-temperature shear layer and to the pressure gradient which is considerably less than pressure gradient for isothermal flow.

The pressure characteristic of dies must be known for use in many technical applications, for instance, to choose work point of extrusion process.

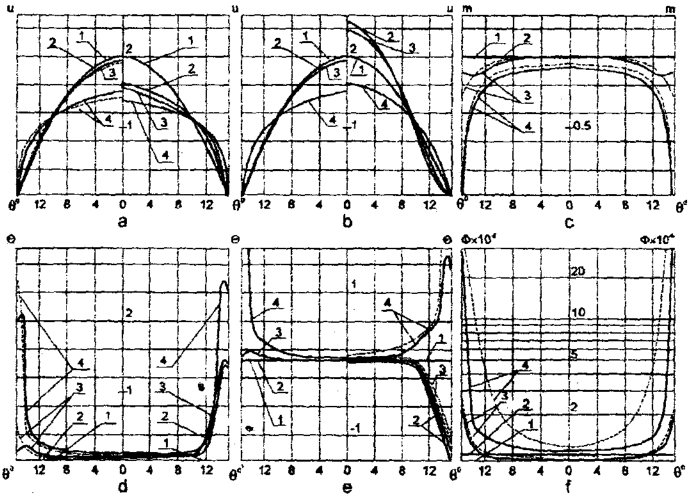

Figure 2. The distributions of dimensionless radial velocity u- a, b); viscosity m- c); temperature Θ -d, e) and dissipation function- f) *vs* the angle. a, d)- left half- for Θ_a = 0, dash-doted line for Bi = 0, right for Θ_a = 1.5; b, e) left half - for Θ_a = 0, right for Θ_a = -1.5, dashed line- for liquid with the constant properties; c, f) for Θ_a = 0. 1- ξ = 1; 2 - 0.6; 3 - 0.2; 4 - 0.0857

Pressure drop- volumetric flow rate dependence for flow of high-viscosity liquids in circular cylindrical channel was investigated in [3].

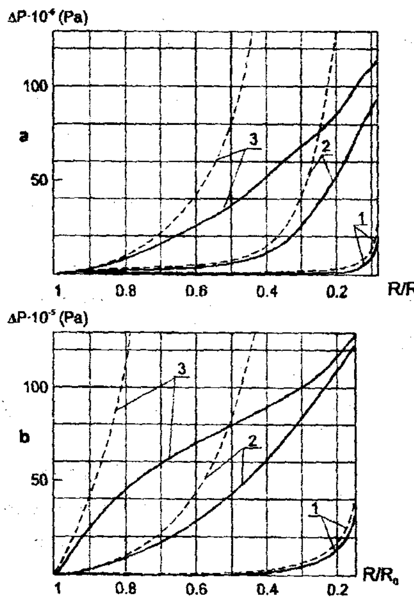

Figure 3. Dependencies of dimension, average on cross- section of confuser pressure drop on radial co-ordinate for confuser with the angles of opening: a) $2\theta_0=30°$; b) $2\theta_0=16°$ and for volumetric flow rate: 1- $Q=6\times10^{-7}$ $m^3 c^{-1}$; 2- $Q=5\times10^{-5}$ $m^3 c^{-1}$; 3- $Q=5\times10^{-4}$ $m^3 c^{-1}$. Solid line- non-isothermal flow, dashed- isothermal.

Pressure- volumetric flowrate characteristic for non-isothermal confuser flow is obtained with different heat exchange boundary conditions, but basis behavior can be seen in flow with adiabatic wall of the channel.

On small flow rate the pressure distribution along the channel is distinguished a little from isothermal distribution (Fig. 3) therefore pressure characteristic is linear here (Fig. 4). With increase of flowrate the small viscosity layer appears at the exit from confuser in consequence of mechanical energy dissipation The pressure gradient on the exit is considerably decreased in comparison with the isothermal (Fig. 3) that leads to nonlinear pressure drop - flowrate dependence (Fig. 4).

The small viscosity shear layer will be extended on more and more part of confuser with further increase of flow rate and the dependence ΔP(Q) will be distinguished more and more from linear (Fig. 3).

For confusers with small angle of opening high-temperature shear layer will have been extended almost on all confuser beginning in some flow rate. It means that high - temperature flow with small pressure gradient has appeared in the channel of confuser. The pressure drop for this flow is decreased beginning with the some flow rate and pressure characteristic with the flow of melts of thermoplastic polymers is non-monotonous (Fig. 4), i.e. it is like the characteristic of non-isothermal flow in the cylindrical channels [4].

It is necessary to note that all presented dependencies are only for steady-state flow.

The criteria of non- isothermal high-viscosity flow in confuser is defined, too.

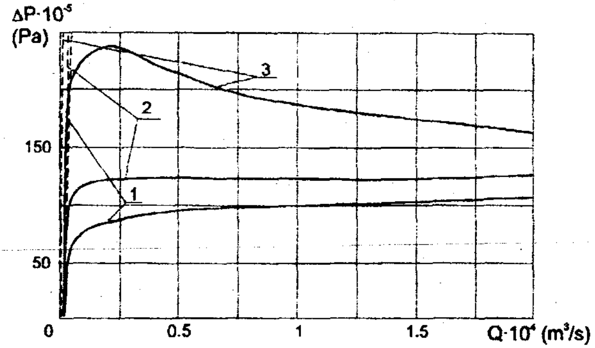

Figure 4. Dependencies of dimension, average on cross- section of confuser pressure drop in confuser with the angles of opening: 1) $2\theta_0=30°$; 2) $2\theta_0=16°$; 2) $2\theta_0=16°$. Solid line- non-isothermal flow, dashed- isothermal.

NOMENCLATURE

a- thermal diffusiviti [$m^2 s^{-1}$], c- specific heat [$J\ kg^{-1}\ K^{-1}$], E- energy of activation of viscose flow [$J\ mol^{-1}$], K- overall heat exchange coefficient [$J\ m^{-2}\ s^{-1}K^{-1}$], P, P_0- pressure, current and inlet [$N\ m^{-2}$], $P_2(\tau)$- Lezhandr's function of first kind and two order, Q- volumetric flow rate [$m^3\ s^{-1}$], R_0,R_1,R- radial spherical co-ordinate, forming of confuser and its truncated part, [m]; R^*- universal gas constant [$J\ mol^{-1}\ K^{-1}$]; T, T_0- temperature of melt, current and inlet [K], V- velocity [$m\ s^{-1}$], x- longitudinal co-ordinate [m], Bi- Biot number, $Gn=\frac{\mu(T_0)V_0^2}{\lambda\Delta T_{rheol}}$- Nahme-Griffith number, Nu- dimensionless heat exchange coefficient between of layers, Pe- Peclet number, $Re=\theta_0\rho V_0 R_0/\mu_0$ - Reynolds number, St_i- Stanton number for i^{th} of layer, λ- thermal conductivity of melt [$J\ m^{-1}\ s^{-1}K^{-1}$], μ- dynamic viscosity of melt [$kg\ m^{-1}\ s^{-1}$], $2\theta_0$ - angle of confuser opening. ρ- density [$kg\ m^{-3}$].

Subscript: a- relating to ambient, i- number of layer, R, θ- radial and angular components of vector.

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