The numerical study of the coextrusion process of polymer melts in the cable head

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Abstract. The process of coextrusion consists in a simultaneous creation of all necessary insulating layers of different polymers in the channel of a special forming tool. The main focus of this study is the analysis of technological, geometrical and rheological characteristics on the values of the layer’s thickness. In this paper are considered three geometries of cable head on the three–dimensional and two–dimensional representation. The mathematical models of separate and joint flow of polymer melts have been implemented by the finite element method in Ansys software package. The velocity fields, temperature, pressure in the cross–sections of the channel and by the length have been obtained. The influence of some thickness characteristics of insulation layers has been identified.

1. Introduction

Today the coextrusion is the most effective method for the manufacture of cable products composed of two or more layers of polymer insulation, the result of which is the high–quality multilayer coating. In this case, the melts of polymers came from different extruders to the cable head, thereby reduced the time of the process, the costs of production, at the same time the quality of the products is increased. In the research papers devoted to coextrusion, the main attention is the influence of technological and rheological parameters on the character of the joint flow of polymer melts [1–4]. However the influence of geometrical parameters isn’t investigated enough, because a conical–cylindrical channel of the cable head was considered without adapter [5–6]. The main aim of this paper is to study the stratified flow of two anomalously viscous fluids in the channel of the extrusion head, which has various spatial geometries, and it is presented in Figure. 1. At the same time the paper focuses on the evaluation of the effect of rheological characteristics on fields of the temperature, pressure and velocity materials and technological characteristics on thicknesses of the layers.

2. Mathematical statement and initial data

In this study, we consider three geometries of a cable head in three–dimensional and two–dimensional representations with channels of different length. Figure 1 shows the configuration of channels of the forming tool, (a) – is a complete three–dimensional model of the cable head with an adapter, the total length is 590 mm; (b) – is the full model, in the flat view, without the adapter, the length of the model is 308 mm; (c), (d) – are truncated models in a three–dimensional and flat view, the lengths of the model are 190 mm; (e), (f) – are truncated models in a three–dimensional and flat view, the lengths of the model are 104 mm. In the following analysis the short notation for models (a–e) are used. The
streams of polymers moving along the channels 1–3 create multilayer covering in the form of 1–screen; 2–insulation; 3–screen. The obtained cable product is shown in Figure 2.

Figure 1. The configurations of cable head of the models (a) (e).

Figure 2. The configuration of cable.

The mathematical assumptions of heat and mass transfer processes in stratified flow the polymer melts are based on the conservation equations. To make the analysis feasible, the process has to be simplified, so thus the following assumptions are made:
- the process is stationary;
- environment is incompressible and there are no elastic properties [7];
- surface forces exceed the mass forces;
- are axisymmetric properties of the flow;
- slip and impermeability conditions are defined at the channel boundaries;
- thermophysical characteristics are constant;

As a result, the mathematical model is a following set of differential equations [8], where each one relates to every layer in the flow:

\[
\frac{\partial (\rho_m v_x)}{\partial x} + \frac{\partial (\rho_m v_y)}{\partial y} + \frac{\partial (\rho_m v_z)}{\partial z} = 0
\]  

(1)
\begin{align*}
\rho \left( V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y} + V_z \frac{\partial V_x}{\partial z} \right) &= - \frac{\partial P}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \\
\rho \left( V_x \frac{\partial V_y}{\partial x} + V_y \frac{\partial V_y}{\partial y} + V_z \frac{\partial V_y}{\partial z} \right) &= - \frac{\partial P}{\partial y} + \frac{\partial \tau_{yy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \\
\rho \left( V_x \frac{\partial V_z}{\partial x} + V_y \frac{\partial V_z}{\partial y} + V_z \frac{\partial V_z}{\partial z} \right) &= - \frac{\partial P}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \\
\rho_c \left( V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right) &= \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \tau_{xx} \frac{\partial V_x}{\partial x} + \tau_{yy} \frac{\partial V_y}{\partial y} + \tau_{zz} \frac{\partial V_z}{\partial z} \\
&\quad + \tau_{xy} \frac{\partial V_x}{\partial y} + \tau_{yz} \frac{\partial V_y}{\partial z} + \tau_{zx} \frac{\partial V_z}{\partial x}
\end{align*}

Where \( P \) – is a pressure; \( T \) – is a temperature; \( \rho \) – is a density; \( C \) – is a heat capacity; \( \lambda \) – is a thermal conductivity; \( \mu_\text{eff} \) – is an effective viscosity; \( \mu_\text{Cons} \) – is the consistency coefficient at temperature \( T_0 \); \( V_x, V_y, V_z \) – the components of the velocity vector; \( I_2 \) – quadratic invariant of the tensor of the deformation rates; \( \beta \) – the temperature coefficient of viscosity; \( n \) – an anomaly of viscosity; \( \tau_{xx}, \tau_{yy}, \tau_{zz}, \tau_{xy}, \tau_{yx}, \tau_{xz}, \tau_{zx}, \tau_{yz}, \tau_{zy}, \tau_{zr}, \tau_{rz} \) – are the normal and tangential stresses [2].

The following boundary conditions are applied on the set of differential equations from (1) to (7):
- Velocity components on fixed walls are equal to zero;
- At the contact boundary of moving conductor, the longitudinal component of velocity is equal to velocity of conductor (0,4m/s);
- The velocity profile is defined (calculated from flow rate) and set at the inlet of the channels;
- The boundary condition of second type of speed and temperature is defined at the output;
- The stationary walls temperature of the channel is 170°C;
- The temperature of polymer melts at the extruder exit is 150°C;
- The temperature of the moving conductor is 110°C;
- At the interfaces of flows polymers is equality of velocities and surface forces;

The properties of polymer liquids are presented in Table 1.

**Table 1.** The rheological and thermophysical characteristics of the materials

| Material | Consistency factor \( \mu_0 \) at \( T=443 \) K, Pa | Temperature coefficient of viscosity \( \mu \), \( 1/K \) | Anomaly index, \( n \) | Density \( c \), kg/m³ | Coefficient of thermal conductivity \( \lambda \), W/(m K) | Specific heat capacity \( C \), J/(kg K) |
|----------|---------------------------------|-------------------------------|-----------------|-----------------|-----------------|----------------|
| Channels material–1,3 Borealis LE0540 | 38523 | 0.0027 | 0.251 | 1080 | 0.182 | 2500 |
| Channels material–2 Borealis LE4421M | 14946 | 0.0168 | 0.542 | 779 | 0.182 | 2500 |
The system of differential equations (1) – (7), supplemented boundary conditions was solved numerically, by the finite element method in the ANSYS software package. The convergence of the solution of the problem with respect to the number of countable iterations and the number of elements in the model has been made.

### Table 2. The nominal thickness.

| Number of channels | 1   | 2   | 3   |
|--------------------|-----|-----|-----|
| Nominal thickness, mm | 0.6 | 3.6 | 0.7 |

### 3. Results and Discussion

The first part of the study focuses on determination of the cable head adapter effect on the heat and mass transfer processes in the forming tool and on the thickness of the resulting multilayer coating. In all the variants of the calculation in the channels the flow rates were set like that the thicknesses of the coatings were created equal to the nominal values. They value are given in Table 3. According to the results presented in Table 4, the values of the thickness layers in models are different : in models (a) the value of thickness completely are consistent nominal significances, by the way in the case by models (b) and (d) the maximal difference is equal 14%. At the same time, for the models (b), (d), (e), this difference is 33%. Thus, the results obtained for the plane models aren't adequate, enough. This makes it difficult to use them in modeling the real processes.

### Table 3. The value of flow rates in channels

| Number of channels | 1   | 2   | 3   |
|--------------------|-----|-----|-----|
| Flow rate (Q), kg/c | 0.021 | 0.09 | 0.017 |

### Table 4. The results of a numerical study for models (a–f)

| Model (a) | Model (b) | Model (c) | Model (d) | Model (e) | Model (f) |
|-----------|-----------|-----------|-----------|-----------|-----------|
| Number of channel | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Layer thickness, mm | 0.6 | 3.6 | 0.7 | 0.7 | 3.3 | 0.9 | 0.7 | 3.5 | 0.7 | 0.7 | 3.3 | 0.9 |
| Maximum temperature, °C | 206 | 188 | 168 | 157 | 156 | 190 | 196 | 180 | 155 | 154 | 155 | 191 |
| Maximum speed, m / s | 2.2 | 1.3 | 2.3 | 2.4 | 2.5 | 1.3 | 2.6 | 1.3 | 2.5 | 1.3 | 2.6 | 1.3 |
| Average temperature in the channels, °C | 168 | 157 | 156 | 190 | 154 | 191 | 155 | 180 | 155 | 154 | 156 | 191 |
| Pressure drop, Pa | 67 | 53 | 47 | 35 | 12 | 30 | 35 | 28 | 22 | 30 | 10 | 13 |

### Table 4. The results of a numerical study for models (a–f)

| Model (c) | Model (d) | Model (e) | Model (f) |
|-----------|-----------|-----------|-----------|
| Number of channel | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Layer thickness, mm | 0.7 | 3.5 | 0.7 | 0.7 | 3.3 | 0.9 | 0.6 | 3.4 | 0.8 | 0.7 | 3.4 | 0.8 |
| Maximum temperature, °C | 196 | 180 | 156 | 154 | 155 | 191 | 191 | 174 | 154 | 152 | 155 | 191 |
| Maximum speed, m / s | 1.5 | 1.3 | 2.6 | 1.3 | 1.3 | 2.6 | 1.5 | 1.3 | 2.6 | 1.3 | 1.3 | 2.6 |
| Pressure drop, Pa | 35 | 28 | 22 | 30 | 10 | 13 | 30 | 11 | 18 | 26 | 7 | 14 |
Figure 3 shows the velocity fields of materials for models (a–e). The maximum speed is developed in the narrowest part of channel 1 in the model (a). Its value is 5 times higher than the speed of the conductor's movement. The maximum difference for axisymmetric and flat models is two times to model (a) and (e); in 1.6 times by model (a) and (b), it's related with into account the effect braking polymer near of the walls. Comparison of the velocities for axisymmetric models (a) (c) and (e) was showed the maximum difference in the maximum speed to 1.6 times for models (a) and (e), which is determined by the different length of the channels. The average speed for axisymmetric models (a, c, e) is approximately 0.75 m/s, for flat models this parameter is 0.62 m/s, the difference is 16%, consequently.

![Figure 3](image)

**Figure 3.** The fields of speeds material for model (a–f).

The images presented in Figure 4 show the steady heating of the material. Nevertheless, it is important to note that the contribution of the forming tool adapter is well illustrated in the analysis of maximum temperatures. The highest temperature is achieved in model (a) and it is equal to 206 °C, while at the same time for model (e), this value was 191 °C. As a result, an increase in the temperature of the materials by 7% is due to contribution of the cable head adapter. Under the similar comparison for models (b) and (f), the difference was 7%. At the same time, while comparing the maximum temperatures in the models (a) – (b), (c) – (d), (e) – (f), the average difference was 8%. It should be noted that for the model (f) the maximum temperature is close to the temperature of the supplied melt, while for model (a) it is 18% higher. This difference comes from the contribution of viscous dissipation, which is well observed for model (a), where the length is almost 6 times higher than in model (f).
Figure 4. The temperature fields in the channels of the forming tool for models (a) – (e).

Since in the polymers processing the rheological properties of the same material can be different significantly, from batch to batch, that the second part of this study focuses on the evaluation of the effect of rheological properties, viscosity in this case, on the thickness of insulation layers. The case was considered when the material of layer 2, was replaced by a material with a viscosity less than twice, at constant flow rates and linear velocity of the conductor. The results for model (a) – (b) are presented in Table 5. In these parts was observed a slight change in the temperature and velocity of the material. However, a significant change was observed for the values of the pressure drop in layer 2. For the model (a), the value decreased by 47% and 41% for model (b), due to the decrease in the viscosity of the material of the 2 layer, the contribution of viscous dissipation decreased, respectively, the polymer material moves along the channel with less force.

Table 5. The results of simulation for layer 2 with viscosity $\mu_0 = 6642$ Pa

|                      | Model (a) | Model (b) |
|----------------------|-----------|-----------|
| Number of channel    | 1         | 2         |
| Layer thickness, mm  | 0.6       | 3.4       | 0.9       | 3.2       | 0.9       |
| Maximum temperature, °C | 202      | 185       |
| Average temperature in the channels, °C | 162      | 156       |
| Maximum speed, m / s | 1.98      | 1.3       |
| Pressure drop, Pa    | 65        | 28        | 36        | 35        | 7         | 28        |
In the second case, when the viscosity of layers 1 and 3 increased 2 times, the results are presented in Table 6. The maximum temperature is increased in model (a) by 13%, and by 4% for model (b), as well as an increase of value pressure drop in layer 1 by 48% and in layer 3 by 30% for model (a), in layer 1 by 50% and in layer 3 by 15% for the model (b).

Table 6. The results of simulation for layer 2 with viscosity $\mu_0 = 74730$ Pa

| Number of channel | Model (a) | Model (b) |
|-------------------|-----------|-----------|
|                   | 1 | 2 | 3 | 1 | 2 | 3 |
| Layer thickness, mm | 0.6 | 3.4 | 0.9 | 0.6 | 3.5 | 0.8 |
| Maximum temperature, °C | 236 | 195 |
| Average temperature in the channels, °C | 154.9 | 152 |
| Maximum speed, m / s | 2 | 1.2 |
| Pressure drop, Pa | 128 | 53 | 68 | 71 | 45 | 35 |

The final part of this work focuses on the determination of the influence of technological parameters, such as the flow rate and the velocity of the material to the thickness of the applied layers. Data dependence the thickness of the layers and mass flow are presented in Figure 5. After the flow rate in channel 1 is increased at 5 times (Figure 5.a), the thickness of layer 1 is increased at 3 times, and the thickness of layer 2 and 3 is decreased accordingly by 30% and 14%. Then the flow rate in channel 2 is increased at 2.5 times, the layer 1 was thinner by 33%, layer 2 was thickened 1.1 times, layer 3 was thinned 57% (Figure 5.b). It the last case the flow rate in channel 3 is increased at 5 times, (Figure 5.c), the thickness of layer 1 isn't changed, layer 2 is decreased by 27%, and layer 3 is increased by 2.4 times. The results are presented for model (a) and (b). The analysis of the results allows to conclude that the effect of flow in channel 3 on the thickness of the layers formed in the other two channels is minimized.

![Figure 5](image-url)
In industry, the question of the possibility increasing the production capacity, therefore, the cases of increasing the moving velocity were considered, and it was necessary to achieve constant values of the nominal thicknesses (Table 2). Figure 6 shows the influence of the linear velocity on the thickness of the layers. We see that the required result is possible at the velocity of the moving conductor is increasing to 0.6 m/s. If the velocity of moving conductor increases by 2.25 times, the thickness of layer 1 is decreased by 1.2 times, the thickness of layer 2 is increased by 2%, and layer 3 is not changed.

Figure 6. The influence of the linear velocity on the thickness of the layers.

4. Conclusion

The results of this study can be applied in the process of analyzing multilayers flows of polymer materials in a forming tool [6]. The main attention should be directed to the contribution of the cable head adapter, the analysis of the results allows to consider the significant contribution of the latter to the processes of heat and mass transfer of anomalous liquids. The obtained data indicates insufficient adequacy of the results of flat moles and, as a result it limits the application. The difference on field’s temperatures and velocities has not exceeded 8%. However, it is necessary to take into account, that the change in the value of the pressure drop in the channel of the forming tool can reach 50%, when changing from one material to another, and all other conditions being equal.

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