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The numerical study of the influence of rheological parameters stratified flows characteristics in cable dies

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Abstract. Today the process of coextrusion is the most technological in the cable production with cross-linked polyethylene, composed of two or more layers of polymeric insulation. Since the covering technology is a simultaneous imposition of all necessary layers (two semiconducting shields on the insulation and conductor and one - on insulation), the main focus of this study is the analysis of significance of various factors influence on stratified flows characteristics. This paper has considered the flow of two abnormally viscous liquids in the cable head. The problem has been solved through a three-dimensional statement by applying the finite element method in the Ansys software package. The influence has been estimated by varying the rheological properties of materials to create all necessary layers thickness.

1. Introduction
There are several characteristics influencing the stratified flow in channels of cable die, such as rheological and thermal properties of materials, technological and geometrical parameters. The main aim in coextrusion process to create thickness set values for all extrusion layers. The object of this research is three geometries of the cable head in a three-dimensional description. Both the influence of geometries of the melt flow channel and the influence of rheological characteristics on the process of the stratified flow are evaluated in this work. The process of the flow of abnormally viscous liquids is described in [1-3].

2. Mathematical modelling
The geometry of the channels of the forming tools is shown in Figure 1-3. The mathematical assumptions of heat and mass transfer processes in the stratified flow of 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 [5];
- 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 simplified model is the following set of differential equations [4], where each channel 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)

\[
\rho_m \left( V_x \frac{\partial N_x}{\partial x} + V_y \frac{\partial N_y}{\partial y} + V_z \frac{\partial N_z}{\partial z} \right) = -\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}
\]  

(2)

\[
\rho_m \left( V_x \frac{\partial N_y}{\partial x} + V_y \frac{\partial N_y}{\partial y} + V_z \frac{\partial N_z}{\partial z} \right) = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}
\]  

(3)

\[
\rho_m \left( V_x \frac{\partial N_z}{\partial x} + V_y \frac{\partial N_z}{\partial y} + V_z \frac{\partial N_z}{\partial z} \right) = -\frac{\partial \tau_{zx}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}
\]  

(4)

\[
\rho_mC_m \left( V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} \right) = \frac{\partial}{\partial x} \left( \lambda_m \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda_m \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda_m \frac{\partial T}{\partial z} \right) + \tau_{xx} \frac{\partial V_x}{\partial x} + \tau_{yy} \frac{\partial V_y}{\partial y} + \tau_{zz} \frac{\partial V_z}{\partial z}
\]
\[
\begin{align*}
\tau_{yy} \frac{\partial V_y}{\partial y} + \tau_{zz} \frac{\partial V_z}{\partial z} + \tau_{yz} \left( \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right) + \tau_{yz} \left( \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right) + \tau_{yz} \left( \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} \right)
\end{align*}
\]

\[
\tau_{xx} = 2\mu_x \frac{\partial V_x}{\partial x}, \quad \tau_{yy} = 2\mu_x \frac{\partial V_y}{\partial y}, \quad \tau_{zz} = 2\mu_x \frac{\partial V_z}{\partial z},
\]

\[
\tau_{xy} = \tau_{yx} = \mu_x \left( \frac{\partial V_y}{\partial x} + \frac{\partial V_x}{\partial y} \right), \quad \tau_{xz} = \tau_{zx} = \mu_x \left( \frac{\partial V_z}{\partial x} + \frac{\partial V_x}{\partial z} \right), \quad \tau_{yz} = \tau_{zy} = \mu_x \left( \frac{\partial V_z}{\partial y} + \frac{\partial V_y}{\partial z} \right).
\]

where \( P \) is pressure; \( T \) is temperature; \( \rho \) is density; \( C \) is heat capacity; \( \lambda \) is thermal conductivity; \( \mu_0 \) is effective viscosity: [2]:

\[
\mu_\epsilon = \mu_0 \exp\left( -\beta(T - T_\theta) \right) \left( \frac{I_z}{2} \right)^{\frac{n-1}{2}}.
\]

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 the moving conductor, the longitudinal component of velocity is equal to the velocity of the conductor (0.4 m/s);
- The flow rate is defined at the inlet of the channels;
- The boundary condition of the 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;

The equations (1) to (7) are solved applying the finite element method in the ANSYS software package. Properties of two materials, Borealis LE 0540 (for shields) and Borealis LE4421M (for insulation), are used in this study. The rheological and thermophysical characteristics of the materials are given in Table 1. The technological parameters are presented in Table 2.

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

| Material                  | Consistency factor \( m_0 \) at \( T=443 \) K, Pa | Temperature coefficient of viscosity \( \nu \), 1/K | Anomaly index, \( n \) | Density \( c \), kg/m³ | Coefficient of thermal conductivity \( \lambda \), W/(m K) | Specific heat capacity \( C \), J/(kg K) |
|---------------------------|-----------------------------------------------|-----------------------------------------------|----------------------|---------------------|-----------------------------------------------|------------------------------------------|
| Material of channels-1,3  | 38523                                         | 0.0027                                        | 0.251                | 1080                | 0.182                                            | 2500                                      |
| Borealis LE0540           |                                               |                                               |                      |                     |                                               |                                          |
| Material of channel-2     | 14946                                         | 0.0168                                        | 0.542                | 779                 | 0.182                                            | 2500                                      |
| Borealis LE4421M          |                                               |                                               |                      |                     |                                               |                                          |

**Table 2.** The technological parameters

| Number of channels | 1     | 2     | 3     |
|--------------------|-------|-------|-------|
| Flow rate (Q), kg/c| 0.021 | 0.09  | 0.017 |
| Nominal thickness, mm | 0.6   | 3.2   | 1.1   |
| Number of channels | 1     | 2     | 3     |
Table 3. The results of simulation modelling for geometry 1, 2 in a three-dimensional description

|                      | The results of simulation for geometry 1 | The results of simulation for geometry 2 |
|----------------------|-----------------------------------------|-----------------------------------------|
| The number of channels | 1                                     | 2                                      |
|                      | 2                                     | 3                                      |
| Layer thickness, mm  | 0.6                                    | 3.6                                    |
|                      | 0.7                                    | 0.7                                    |
| Maximum temperature, °C | 202.6                                 | 196                                    |
| The average temperature in the channels, °C | 168.5                                 | 155.9                                 |
| The maximum speed, m / s | 1.86                                  | 1.54                                  |
| Pressure drop, Pa (the difference between pressures in outflow and inflow) | 6.7·10^7 | 5.3·10^7 |

Table 4. The results of simulation modelling for geometry 3 in a three-dimensional description

|                      | The results of simulation for geometry 3 |
|----------------------|-----------------------------------------|
| The number of channels | 1                                     |
|                      | 2                                      |
|                      | 3                                      |
| Layer thickness, mm  | 0.6                                    |
|                      | 3.5                                    |
|                      | 0.8                                    |
| Maximum temperature, °C | 191                                    |
| The average temperature in the channels, °C | 154.9                                 |
| The maximum speed, m / s | 1/33                                  |
| Pressure drop, Pa (the difference between pressures in outflow and inflow) | 3.57·10^7 | 1.25·10^7 |

The maximum temperature of the melt in channel 1 is 3.5% higher than in channel 2, and 5.7% higher than in channel 3. The average temperature in channel 1 is 8% higher than in channel 3. It can be concluded that the geometry of channel 1 significantly influences the melt temperature.

Also the calculation has been done to estimate the influence of rheological properties (in this case viscosity) for the thickness layers. In the first case, the viscosity of insulation material has been reduced by 2.25 times. As a result, there is a slight change in the temperature and velocity of material movement. The drop pressure in channel 2 has been decreased by 2.54 times for geometry 1, by 3.95 times for geometry 2, and by 2.19 times for geometry 3, regarding the case of a three-dimensional description.

In the second case, the viscosity of the material shields has been increased twice. As a result, the highest alterations have been obtained for the maximum temperature of the melt. In average, it was increased by 14% for each of the geometries in the three-dimensional description.

3. Conclusion
The results of this research can be applied in the process analysis of flows in cable heads [6]. The main attention should be paid to the channel geometry: the shorter the length, the lower the precision of the results.
The difference in field’s temperatures and velocities has not exceeded 8%. However, the most significant part is a drop pressure, as it must be taken into account for designing the technological equipment.

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