

Simulation, extrusion, mini-tube, head

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NUMERICAL SIMULATION OF THE DESIGN OF EXTRUSION PROCESS OF POLYMERIC MINI-TUBES

Abstract

In this paper we represent a study reporting the numerical simulation of small-diameter pipes extrusion process. Polypropylene and low density polyethylene were chosen as plastics and a selected transverse head as a tool in the simulations. The aim of the study is to examine the distribution of temperature in the individual sections of the bagasse and tools, in order to optimize the parameters and process flow extrusion and validate the implementation tools, by simulating the flow of plastic by the head.

1. INTRODUCTION

Modern plastics are used in various branches of technology, and currently are used daily around the world. The term plastic is used for the material and the basic component to determine its properties and structure is a polymeric chain. From a chemical point of view, polymers are a chemical substance of natural origin, synthetic (manufactured in chemical synthesis), modified by the addition of chemical excipients such as stabilizers or plasticizers. The low cost of production, good physical and chemical properties relative to other materials, and good strength properties in relation to low density plastic, have an impact on their increasing usage as a replacement for materials construction such as steel. The ability to change their properties and characteristics in the right conditions has an impact on their extensive use in the processing of polymers on a global scale, such as extrusion or injection.

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For precise selection of the extrusion process conditions, it is necessary to examine the technological properties of thermoplastics, the most important of which are indicators of the speed of flow: mass and volume. Flow rate indicator is a factor that defines the thermoplastic materials, because it determines their vulnerability to changes in physico-chemical structure and properties (Garbacz, 2012; Jachowicz & Klepka, 2012; Klepka, Jeziórska & Szadkowska, 2015; Pieliowski & Pruszyński, 1998; Sikora, 2006).

During the extrusion process, derived products may have different forms depending on the type of process and tools. In the process of extrusion of pipes are used special tools, which is the initial shape of the flowing material in the form of the head, which may be linear or transverse (Klepka, 2001; Rabek, 2008; Rydzkowski, 2011).

The characteristic feature of the extrusion is tempering materials under high temperature, push it through the channels of the tools, then rapid cooling in order to harden the resulting bagasse. Depending on the requirements of the requirements of extrudates there are less or more complex technological lines (shown in Figure 1)(Garbacz & Sikora, 2012; Jachowicz & Klepka, 2012; Tor-Świątek, Garbacz & Jachowicz, 2016):

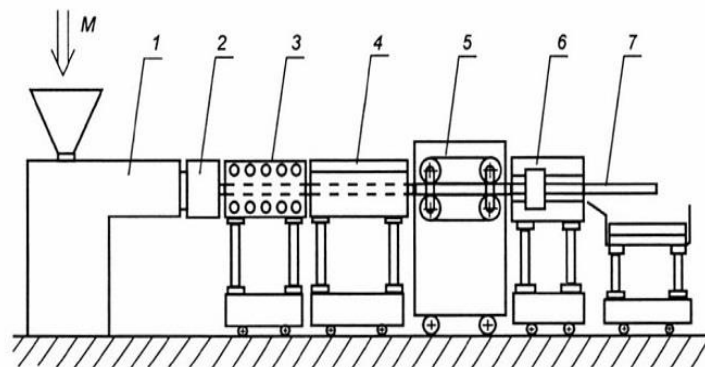


Fig. 1. Diagram of the line leading to the extrusion of pipes. M-polymer material, 1 – extruder, 2 – head, 3 – calibrator, 4 – cooling device, 5 – receiving device, 6 – shut-off device, 7 – extrudate (“Wytłaczanie - linia technologiczna”, 2018)

The basic elements of the extrusion line are extruder that includes elements such as a cylinder, a snail with radiators which are plasticizer system, forming tools, such as the head and calibrator, and cooling baths constitute an additional element of the line.

Extrusion head is called the simple device mounted at the end of the cylinder, ended with an extrusion nozzle. As a result of the occurrence of different types of polymer flow direction in the head there are linear and transverse heads. The selection of the head depends on the shape of what we want to get in the end.

For example, a polymer tubes, extruded are using head linear or transverse. Sample diagram of head is shown in Figure 2 (White & Potente, 2003; Sikora, 1993, 2006; Sikora, 2008).

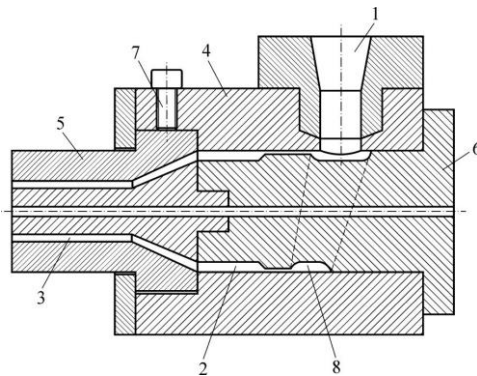


Fig. 2. Diagram of the transverse extrusion head; 1 – inlet channel, 2 – annular distributing channel, 3 – die, 4 – main body of the extrusion head, 5 – die body, 6 – heart-shaped mandrel, 7 – adjusting bolt, 8 – manifold

Other elements which form part of the extrusion line are the calibrators, cooling baths, and extraction. All these elements are responsible for the shape, dragging a plastic head for subsequent line items, and the final product as a result of temperature changes that occur in the solidification between the cooling bath and plasticized material. The change in temperature in the extrudate can be realized by immersion in a hot tub with a coolant (usually water), through the compressed air cooling (blowing) or ambient air (at room temperature) (Rauwendaal, 2014; Sasimowski, Sikora & Królikowski, 2014).

2. NUMERICAL SIMULATION IN THE PROCESSING OF POLYMERIC MATERIALS

With the development of numerical simulation techniques, the tools to carry out the process simulation of polymer extrusion process, in order to optimize the process, starting with the design of the tools by asked the process parameters, to define the conditions after leaving bagasse extrusion head. Thus, it is possible to carry out the entire process of extrusion in "virtual reality", in accordance with the data in order to validate the intended process.

There are several systems to design processes such as extrusion or injection. There is a division of universal and special software. Special simulation systems include MOLDFLOW, CADMOULD whether MOLDEX3D. A general software used to simulate processes is the SolidWorks CAD system, which is a simple

effective tool to design the tool parts, assemblies, components, the execution of the drawings, and then carrying out the tests simulation on the component (Githuku & Giacomini, 1993; Koutelieras, Kioupi, Haralampous, Kitsakis, Vaxevanidis & Kechagias, 2017; Sykutera, 2012).

To simulate the Flow Simulation a tool based on a method of CFD (computational fluid dynamics) has been utilized. This technique allows to perform a flow analysis for liquids or gases. Process simulation involves several steps (fig. 3) (Wilczyński, Garbarski, Nastaj & Lewandowski, 2009):

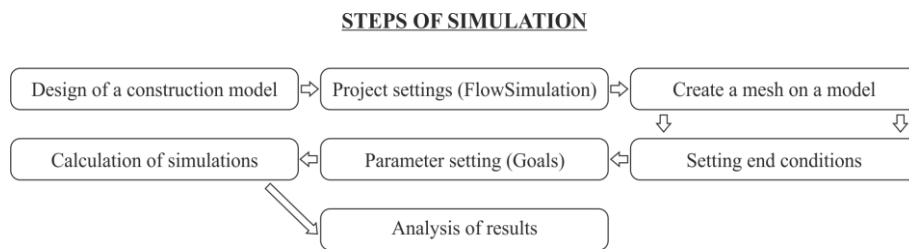


Fig. 3. Stapes of simulation in the Flow Simulation module

3. MATERIALS AND METHODS

3.1. Simulation Techniques

Our principal aim in this research is to analyze the flow temperature in the cylinder and the flow of plastic and to simulate the process of extruding a small diameter pipe, in order to analyze the process and select the optimal process parameters.

In order to analyze the temperature of the material during heating and cooling, a cylinder with a nozzle was designed in the SolidWorks 2015 (Fig. 4). The dimensions of the nozzle are 2.00 mm, length 6 mm, with a flow channel diameter 4.50 mm, and a total length of 180 mm, with a built-in core 180 mm long.

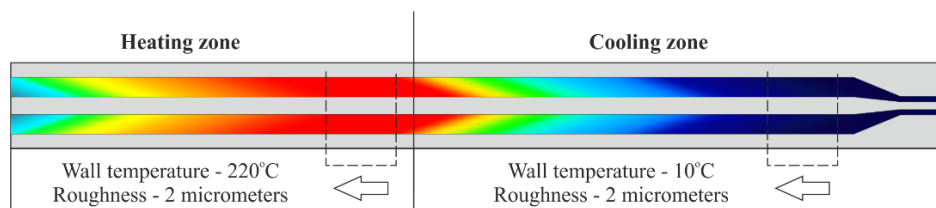


Fig. 4. Diagram of temperature distribution in the cylinder used for flow simulation

In order to obtain the results of temperature distribution in the cross-section of the material flowing through the cylinder channel at high temperature, the model has been divided into two main zones: heating and cooling.

The temperature in the zones was successively: in the heating zone: 185°C, 205°C, in the cooling zone: 225°C, 15°C, 25°C, 35°C. It was assumed that the temperature of the material at the inlet is 25°C. The factors investigated were the external temperature of the fluid, the internal temperature of the fluid and the temperature of the core. The variable factor was the temperature of the walls, and the constant factors were: the temperature of the material at the inlet, the pressure, the flow velocity and the roughness of the walls.

To simulate the mini-tube extrusion a transverse head was designed. The head was connected to the cylinder (Fig. 5, 6) through which plasticized plastic flows. One of the most important elements of the head design is the splitter connected to the core, which allows, as a final effect, to obtain the product, with a circular shape in the form of a mini-tube. The purpose of the simulation process of mini-tube extrusion is:

- analysis of the transverse head construction (checking the flow of the material inside the head),
- simulation of plastic flow at high temperature,
- analysis of fluid properties after the nozzle outlet.

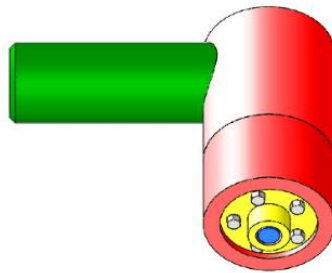


Fig. 5. Construction of an transverse extrusion head

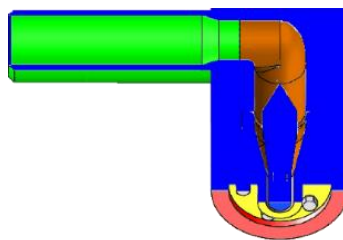


Fig. 6. Cross-section of an transverse extrusion head

3.2. Plastic materials

Two polymer materials were selected for the tests: Polypropylene (PP) under the trade name MoplenEP440G from Basell Orlen and Low Density Polyethylene (PE-LD) under the trade name Malen E FGAN 23-D006 from Basell Orlen. The properties of the materials used during the simulation are shown in Table 1.

Tab. 1. Properties of plastics used in the simulation process

Properties	Polypropylene	Polyethylene	Unit
Density	900	925	kg/m ³
Specific heat	1700	2200	J/(kg K)
Thermal conductivity	0.4	0.45	W/(m K)
Mass flow index	1.3	0.75	g/min
Melting point	150	114	°C

The parameters and variables used in this work for extrusion simulation are shown in Table 2.

Tab. 2. Parameters the extrusion simulation

Evaluated parameters	<ul style="list-style-type: none"> - Temperature of the material in the nozzle - Material temperature after outlet from the nozzle - Plastic pressure in the nozzle - Plastic pressure after the nozzle outlet
Variable parameters	<ul style="list-style-type: none"> - Temperature - Flow speed
Fixed parameters	<ul style="list-style-type: none"> - Temperature of the material at the inlet to the cylinder - Pressure - Flow rate - Curiosity of walls - Cooling at the outlet - Load

3.3. Simulation of plastics flowing in the cylinder

The cylinder model described in the test program was used to analyze the flow of plastic in the cylinder to analyze the temperature distribution. In order to properly define the flow of selected materials in the cylinder, boundary conditions were given:

- temperature of the material at the inlet (25°C),
- wall temperature in the heating zone (185°C, 205°C, 225°C),
- wall temperature in the cooling zone (15°C, 25°C, 35°C),
- flow speed (10 m/s),
- wall roughness (2 μm).

The temperature distribution during heating and cooling is shown in the cross-section drawing, on which points were placed along a radius of 4.5 mm, defining the internal temperature of the fluid, the core temperature and the external temperature of the liquid, respectively (Figure 7).

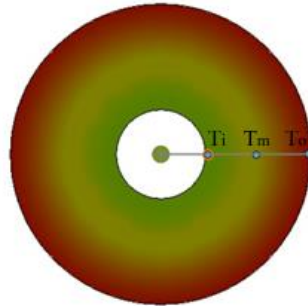


Fig. 7. Distribution of points along the diameter of the cross-section.
T_i – Inner temperature, T_m – Middle temperature, T_o – Outer temperature

For each of the points placed on the radius at a distance from the point of the cross-section, the values of the fluid's temperature along the length have been generated using the Point parameter tool:

- T_i, at a distance of 1.5 mm from the center point,
- T_m, at a distance of 3.0 mm from the center point,
- T_o, at a distance of 4.5 mm from the center point.

3.4. Simulation of the mini-tube extrusion process

In order to simulate the extrusion of mini-tube through the heads, the basic boundary parameters for and for polyethylene were generated. The flow was defined as laminar, internal, and isothermal for non-Newtonian liquids at temperatures of 240°C for polypropylene, and 200°C for polyethylene, respectively.

In order to a more accurate analysis of the simulations, the following boundary parameters were given:

- wall temperature (200°C, 240°C),
- inlet load (22 N),
- flow speed (10 m / s)
- wall roughness (1.2 μm),
- cooling at the outlet (25°C).

4. RESULTS AND DISCUSSION

The temperature distribution of polypropylene and polyethylene during the heating process are depicted have been calculated the results are depicted in Tables 3 and 4, respectively. We have simulated a series of three different temperatures: 185, 205 and 225°C. As it was expected the temperatures T_o , T_m and T_i increase with the increasing temperature. It is interesting to note that in every case, the polyethylene samples show a higher temperature than the analogue simulation of polypropylene due to the higher conductivity of the polymeric matrix.

Tab. 3. Temperature distribution during heating for polypropylene (PP)

185°C			205°C			225°C		
T_o	T_m	T_i	T_o	T_m	T_i	T_o	T_m	T_i
180.20	142.19	121.75	199.65	155.85	132.85	219	173.45	148.33

Tab. 4. Temperature distribution during heating for polyethylene (PE-LD).

185°C			205°C			225°C		
T_o	T_m	T_i	T_o	T_m	T_i	T_o	T_m	T_i
181.83	156.22	141.91	205.02	169.86	158.11	222.03	189.02	169.90

In Figure 8, we have also presented the temperature distribution of our samples during the heating process. In agreement with the previous results, the temperature distribution of polyethylene is more uniform in comparison to polypropylene and higher values of T_i are reached for PE-LD when polymers are heated.

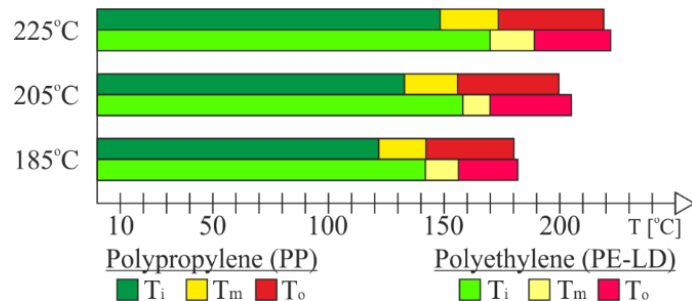
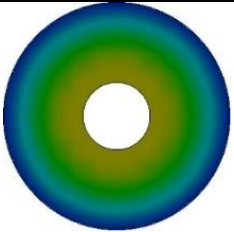
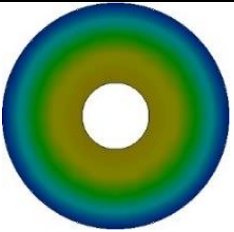
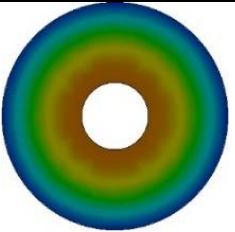
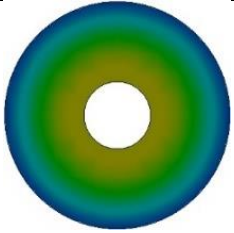
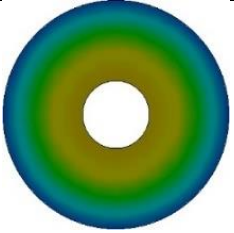
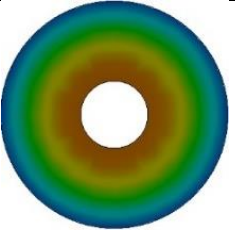
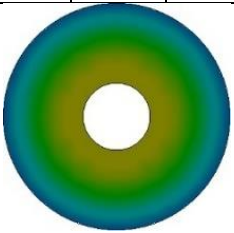
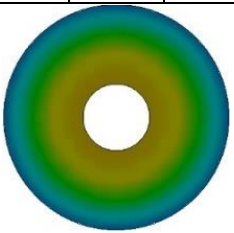
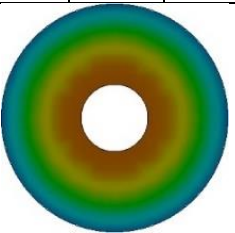


Fig. 8. Temperature graph in measuring points, for PP and PE-LD, during heating

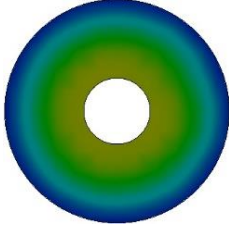
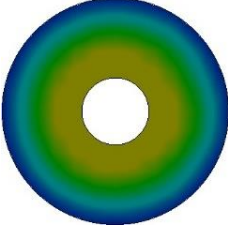
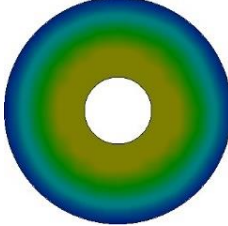
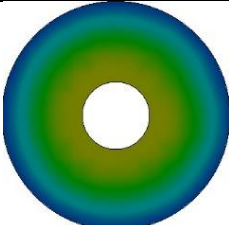
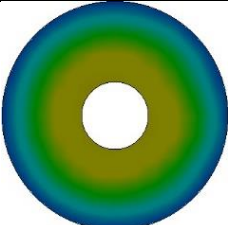
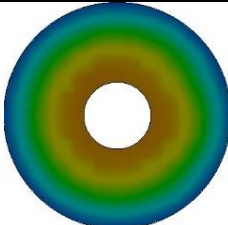
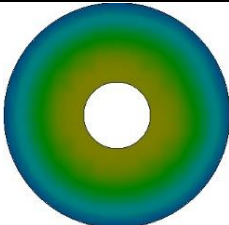
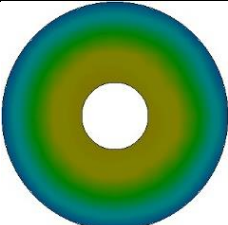
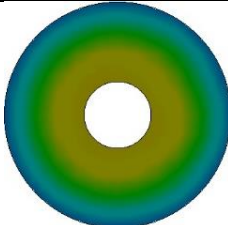
We have performed an analogous study with our samples during the cooling process in the extrusion. The results of the simulation of the temperature distribution during cooling for polyethylene and polypropylene are presented in Tables 5 and 6. Three different cooling temperatures have been evaluated (15, 25 and 35°C) for the three heating temperatures studied in the previous section. As expected, the cooling temperature has a big impact on the values of T_o . With the decrease of the cooling temperature, lower T_o values are calculated. In the case of PP, the values of T_o are slightly lower compared to PE-LD. Regarding the values of T_i for PE-LD, the lower values of cooling temperature decrease significantly the values of T_i as it was expected due to the conductivity of this polymer. Interestingly, the values of T_i are not affected by the cooling temperature for the PP samples. As it was shown in Table 1, the thermal conductivity of PP is 0.4 W/m·K and 0.45 for PE-LD. This small difference in this parameter generates a very different behavior of the temperature in the inner layer of the extrusion profile during the cooling process.

In addition, we have studied the influence of the length of the radius (measuring point) on the temperature distribution. All these data are collected in Figure 9.

Tab. 5. Temperature distribution during cooling for polypropylene (PP) at temperatures of 15°C, 25°C, 35°C.

	185°C			205°C			225°C		
15°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	31,12	120,5	162,12	31,4	137,33	176,68	35,12	149,25	193,65
25°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	39,11	128,02	160,66	41,21	138,97	177,53	44,02	152,34	194,36
35°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	48,12	131,21	164,01	49,89	142,89	179,11	52,13	156,19	196,24

Tab. 6. Temperature distribution during cooling for polyethylene (PE-LD), at temperatures of 15°C, 25°C, 35°C

	185°C			205°C			225°C		
15°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	31.15	124.21	156.01	34.11	137.05	170.98	34.86	152.03	188.21
25°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	40.85	128.21	157.17	44.12	141.97	173.44	45.71	154.2	189.12
35°C									
	T _o	T _m	T _i	T _o	T _m	T _i	T _o	T _m	T _i
	49.87	132.32	158.5	52.34	145.44	175.11	48.12	142.92	175.32

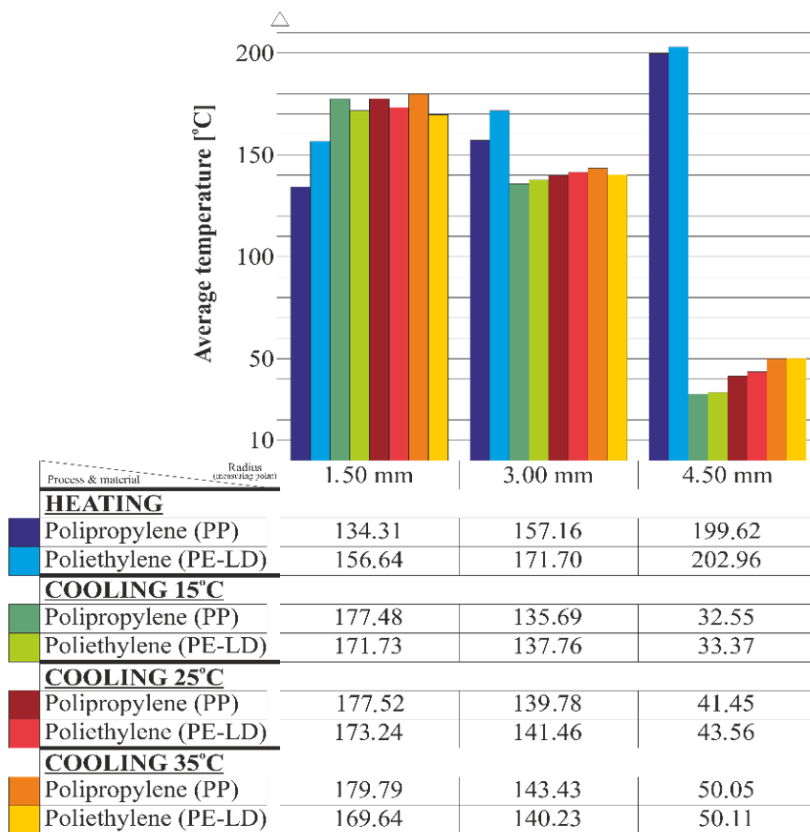
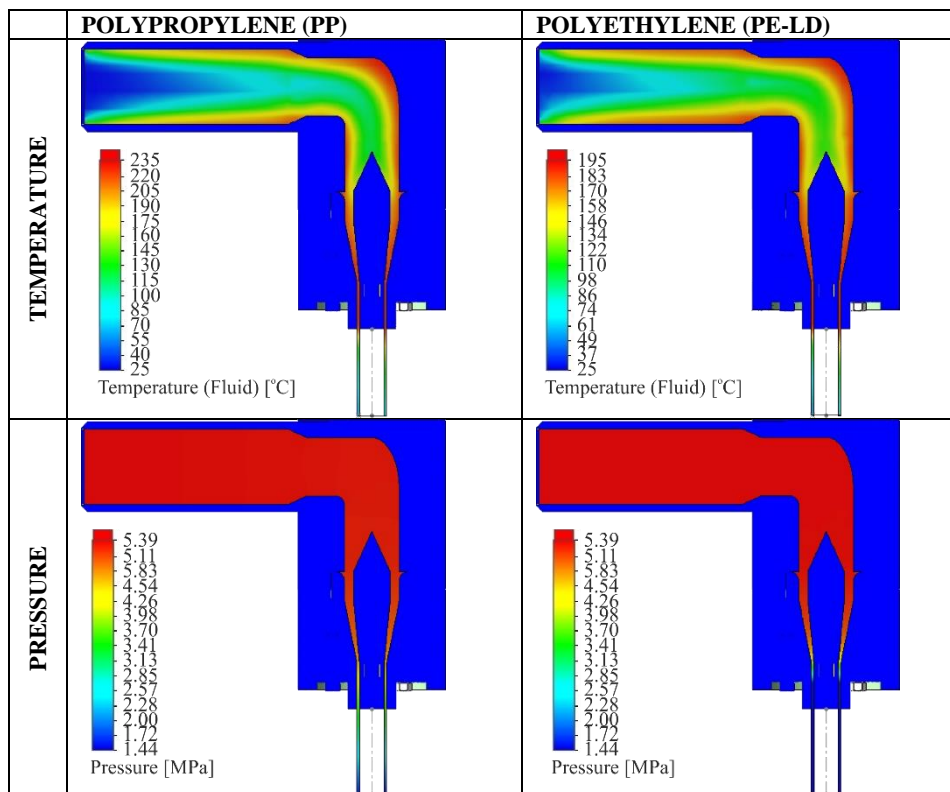


Fig. 9. Average values of the temperatures of the inner layer, the core and the outer layer.

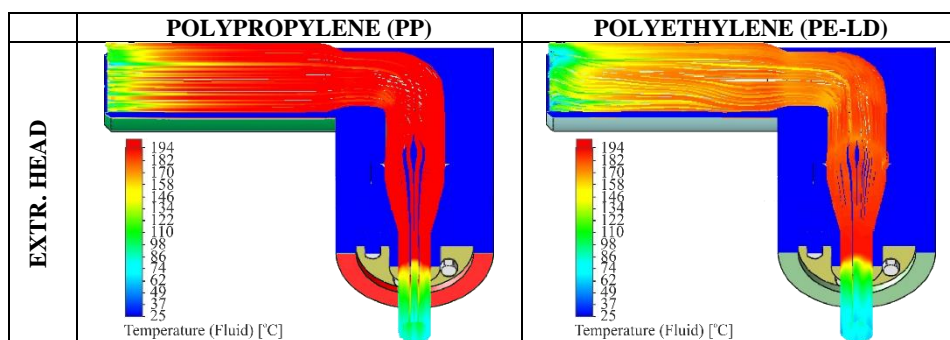
It can be seen that increasing values of the radius provokes higher temperatures in the heating zone and lower temperatures in the cooling zone regardless the material and extrusion conditions studied. In the heating area, the differences between PE-LD and PP are decreased at longer radius. Our hypothesis is that for such a long distance the thermal conductivity values of 0.4 and 0.45 W/m·K are not able to induce a different behavior in the flowing material. In agreement with this statement, the cooling temperature is a parameter with a remarkable impact on the temperature profiles at large values of radius.

Finally, based on the conducted simulations of the polymer extrusion process, using the transverse head for extruding mini-tubes, the pressure and temperature distribution values were read out during the flow of the material through the tool and the distribution of the flow trajectory was illustrated. The final results of the extrusion simulation of polypropylene and polyethylene are presented in Table 7 and Table 8.

Tab. 7 . Temperature and pressure distribution for polypropylene and polyethylene



Tab. 8. Distribution of flow trajectory for polypropylene and polyethylene



5. SUMMARY AND CONCLUSIONS

In this paper we have shown that numerical simulations are a basic tool for solving many problems in various technical fields, specifically in the flow conditions of plastic extrusion. We have proved that basic simulation software such as Solid-Works and MOLDFLOW allows us to rapidly evaluate the extrusion conditions for different kinds of polymers, heating and cooling temperatures and extruding heads. In our case, we have evaluated the influence of these extruding conditions on the processing of polyethylene and polypropylene in order to manufacture mini-tubes. The outer, core and inner temperature has been calculated for three different heating temperatures (185, 205 and 225°C) and cooling temperatures (15, 25 and 35°C). The higher thermal conductivity of PE-LD provokes higher inner temperatures compared to PP in the heating zone. In the cooling zone, the temperature affects more significantly the values of the outer temperature. Surprisingly, the values of T_i of PP do not change with the cooling temperature, however, there is a big impact on T_i values for PE-LD. When the length of the radius (measuring point) is evaluated, we have demonstrated that with larger values of radius the thermal conductivity barely affects the average temperature in the heating zone, however in these conditions the cooling temperature is a relevant parameter which must be taken into account in the design of the extruding process.

With this study, we have the opportunity to evaluate the main parameters of the processes that occur inside the extruder, including the head itself. This allows us to optimize the design of the tool in order to get the most accurate reproduction of the extrudate. Correctly performed numerical simulations, together with a reliable interpretation of results, allow to avoid errors during the design of both the tool and the process (including parameters) of extrusion leading to a reduction of time and costs.

Acknowledgments

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