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Dedicated to the memory of
Academician Dr. Eng. Emilian BRATU (1904–1991)

HEAT TRANSFER SIMULATION FOR INJECTION MOLDING OF POLYLACTIC ACID PARTS

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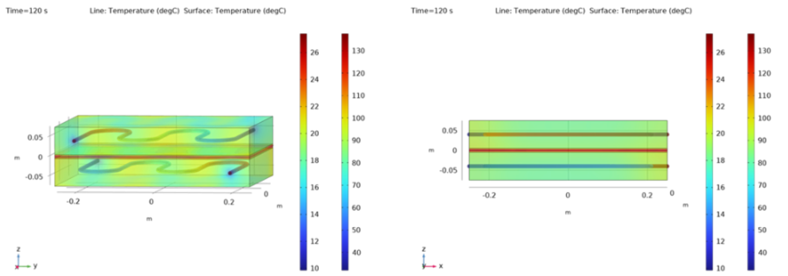

Biodegradable and biocompatible polymers represent an excellent alternative to conventional polymers for various applications. One of the most promising biopolymers is represented by polylactic acid (PLA). During injection molding process, the cooling stage has a great importance because it ensures the dimensional stability of the produced articles. In this simulation study regarding the cooling process in the injection molding of PLA, with cold water, it was analyzed the temperature distribution in the mold-material system in the case of a polymeric plate and the cooling time was calculated. The model of heat transfer was solved in COMSOL Multiphysics software, by defining the geometry of the mold, the materials properties and the cooling conditions.

INTRODUCTION

As an important manufacturing technique, processing about 117 million metric tons of thermoplastic materials each years,[1] the injection molding is used especially to produce articles with complex shape and requiring high dimensional precision[2] at low cost.

Injection molding is a complex cyclic process, and it was intensively investigated by experimental and theoretical studies in the last years. The interest of researchers in the fields of polymer science and chemical engineering was concentrated on mold filling, compression, solidification and cooling processes.[3,4] The study of the heat transfer in the cooling stage presents a great importance in this manufacturing technique, because at least 60% of the defects observed in the injected articles, such as wrapping, can be correlated with the inefficiency of the cooling system.[5] On the other side, the reduction of the cooling time, which represents about 50 to 80% of the total cycle time,[4] will considerably increase the production rate.[6] In the cooling stage, the heat transfer is realized with air, water (commonly used), mixtures of water-ethylene glycol or oil. Because in the case of liquids, the cooling agent circulates through a circuit of channels in the mold, the design of cooling circuits must assure uniform

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cooling, which has a great influence on the dimensional stability of the final product.[5,6] The uniformity of cooling can be characterized by the temperature distribution in the mold, established by the simulation of the heat transfer processes during the solidification and cooling of the injected article.[7,8] The traditional cooling circuits are represented by straight channels,[6] but serial circuits and parallel circuits are often used in the industrial practice.[5] The cooling channels manufactured following the product topography are known as conformal cooling,[5,9] which represents the actual type of cooling system in injection molding.[10]

In the last years, a great part of the plastic industry was occupied by the production of biodegradable and biocompatible polymers derived from renewable sources, which represent an excellent alternative to conventional polymers obtained from crude oil and natural gas.

One of the most promising biopolymers is the polylactic acid or polylactide (PLA), an aliphatic polyester, thermoplastic, eco-friendly, characterized by good mechanical properties and also by law thermal stability, high moisture sensitivity, and low solvents resistance.[2,11] This polymer has many applications in food industry, fibers, medical practice (orthopedic and fixation devices, tissue engineering and regenerative medicine, drug delivery systems).[12,13] PLA can be processed by many technologies, but a high number of products are realized by injection molding.

This paper presents the results of a simulation study of the heat transfer during the cooling stage of PLA injection molding, using water as cooling agent. The model of heat transfer was solved in COMSOL Multiphysics software, by defining the geometry of the mold, the materials properties and the cooling conditions. It was analyzed the temperature profile in the mold-material system and the cooling time was calculated.

PHYSICAL MODEL

In the analysis of mold cooling, the design of cooling channels is very important as they can insure a uniform cooling[1]. In the present study it was considered a simple geometry of the PLA object, a plate 1 cm thick and consequently the geometry of the mold with the cooling channels was a standard one, recommended for simple objects. The diameter of the tubes was considered 1 cm.

The geometry of the mold block with the cooling channels is presented in Fig. 1.

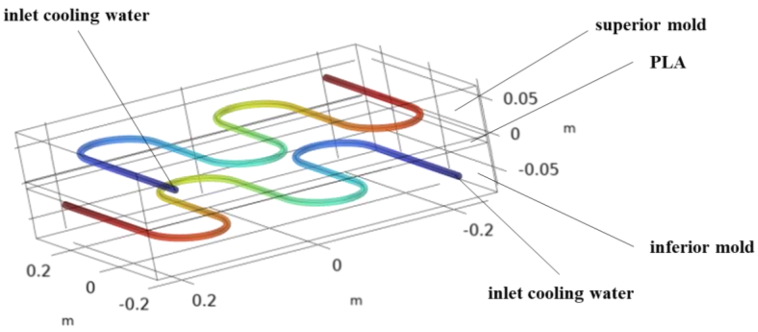


Fig. 1 – Geometry of the mold, PLA slab, and cooling pipes

The inferior and superior parts of the mold and cooling pipes are made of steel and to ensure a more efficient cooling regime the water flows in countercurrent in the two pipes. The properties of the steel and water are defined from the COMSOL Multiphysics database and for the PLA domain are defined as function of temperature as in previous work.[8]

MATHEMATICAL MODEL

For the water flow in the cooling channels in COMSOL is used the ***Nonisothermal Pipe Flow*** physics using the equations for the momentum and mass conservation:

$$\rho \cdot \frac{\partial u}{\partial t} = -\nabla p - f_D \cdot \frac{u^2}{2 \cdot d} \cdot \rho \qquad (1)$$

$$\nabla \cdot u = 0 \qquad (2)$$

along with the energy conservation equation

$$\rho \cdot c_p \frac{\partial T}{\partial t} + \rho \cdot c_p \cdot u \cdot \nabla T = \nabla \cdot \left(k \cdot \nabla T \right) + Q_{wall} \qquad (3)$$

where c_p is the heat capacity, J/(kg·K); ρ – density, kg/m^3; T – temperature of cooling water, K; k – thermal conductivity, W/(m·K); u – velocity field, m/s; f_D – Darcy friction factor; t – time, s;

Q_{wall} – heat rate changed between cooling water and the mold, W/m^3.

For the rest of geometry in COMSOL is used the ***Heat Transfer in Solids*** physics, governed by the heat conservation law and heat transfer equations

$$\rho \cdot c_p \cdot \frac{\partial T_2}{\partial t} = \nabla \cdot k \cdot \nabla T_2 \tag{4}$$

where T_2 is temperature in solids, K

The heat exchange through the pipe wall is described by the equation:

$$Q_{wall} = h \cdot \left(T_{ext} - T\right) / L \tag{5}$$

where h is the heat transfer coefficient, $W/(m^2 \cdot K)$; L – perimeter of the pipe, m; T_{ext} – external temperature outside of the pipe, K; T – temperature of the cooling water, K.

The inlet temperature of the cooling water was 10 °C and the cooling water flow rate was 10 L/min.

The initial temperature of PLA was 180 °C.

For the convection in the surrounding air a heat transfer coefficient of 2 $W/(m^2 \cdot K)$ was considered.

RESULTS AND DISCUSSION

The duration of the cooling simulation was considered till the mean temperature in the PLA volume is around 60 °C, and consequently about 500 s proved to be sufficient (Fig. 2). The relative long duration is justified by the operating conditions assumed: the high thickness of the PLA slab, and the initial temperature of the mold, corresponding to crystalline PLA (100 °C).[14]

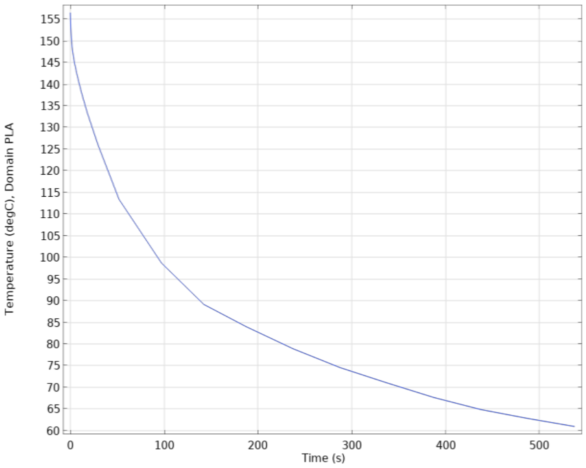
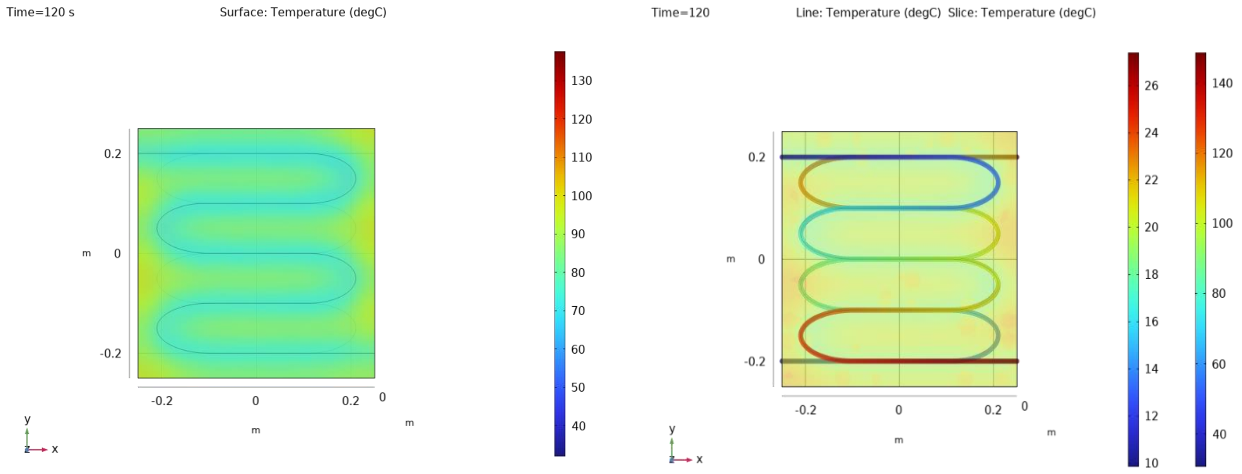


Fig. 2 – Variation of mean temperature in PLA volume.

The time and space temperature variations are represented in Figs. 3–6.



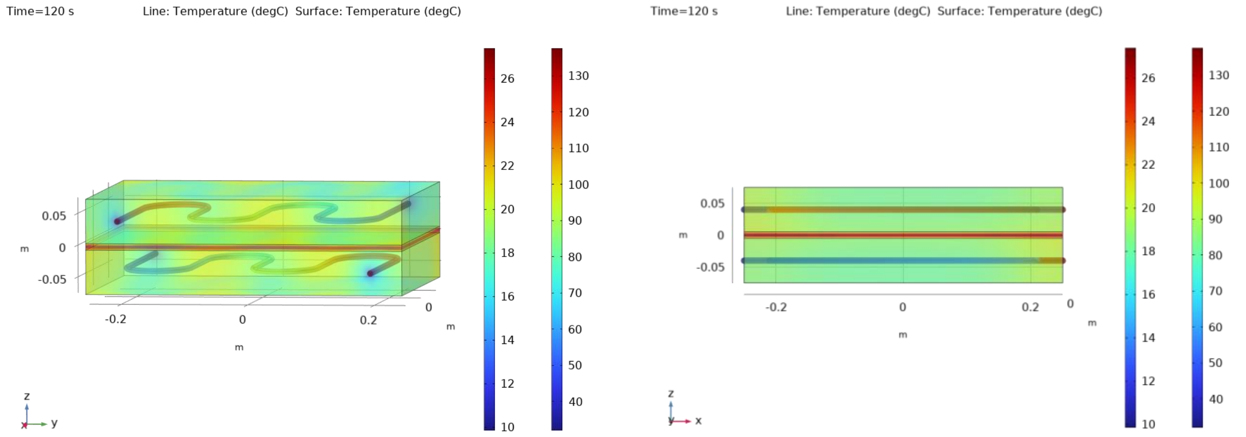
a

b

Fig. 3 – Temperature profiles after 120 seconds: a) mold superior surface; b) cooling water temperatures (line) and upper surface of the PLA slab (slice).

In time, the mold surface begins to cool (Fig. 3a) and the PLA slab presents a similar temperature profile (Fig. 3b). As can be seen in Fig. 3b, the temperature of the cooling water increases with 16 °C, and the temperature of PLA surface decreased at around 100–110 °C. The lowest temperature values are in region where the cold water enters in the upper pipe.

After 120 s can be seen that in the middle of the PLA slab is still at a high temperature (around 130 °C), but near to the steel contact surface the temperature is lower.

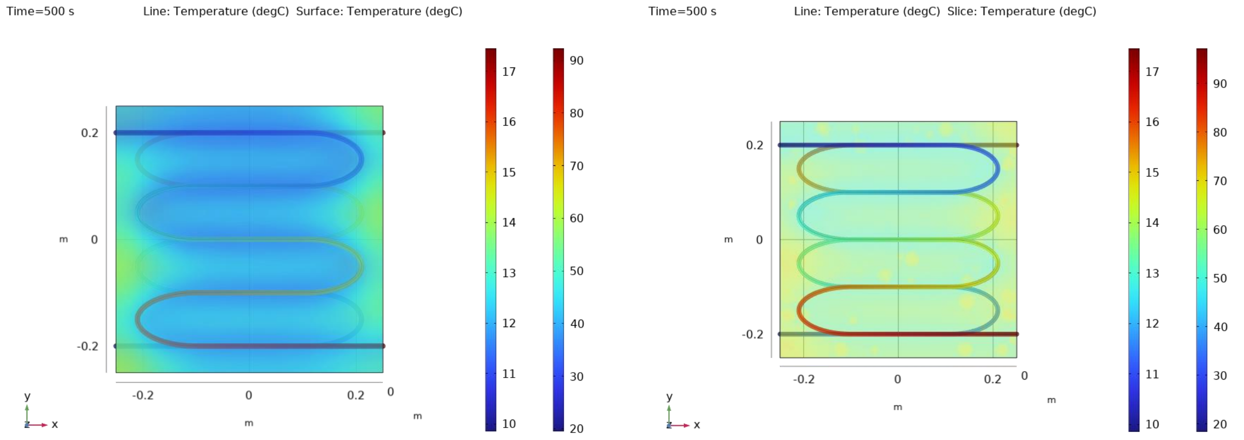


a

b

Fig. 4 – Temperature profiles after 120 seconds: a) perspective view in the cooling pipes (line) and in the mold (surface); b) frontal view of the cooling pipes (line) and the mold (surface).

Figure 5 presents temperature profiles after 500 s, proving both mold and PLA slab have lower temperatures and the increase of cooling water temperature is only 7 °C, standing for a lower heat transfer rate.

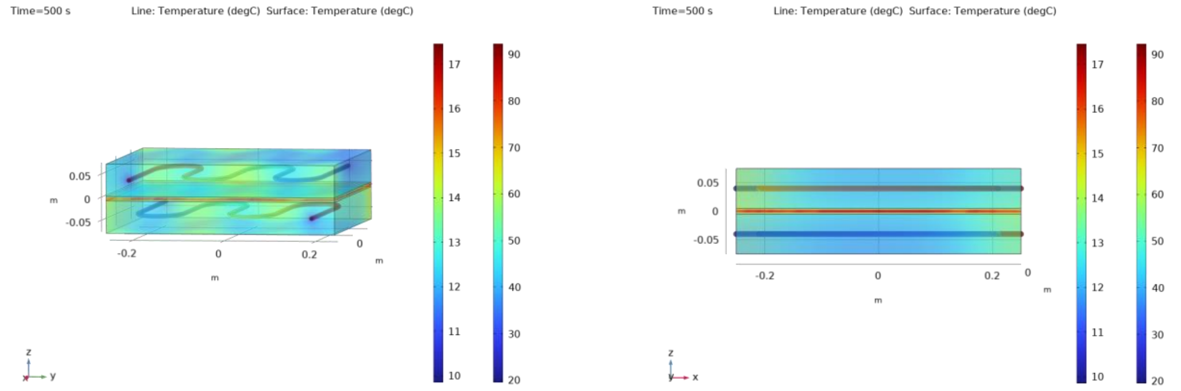


a

b

Fig. 5 – Temperature profiles after 500 seconds: a) mold superior surface; b) cooling water temperatures (line) and upper surface of the PLA slab (slice).

Figure 6 presents temperature profiles after 500 s on a front view of the mold. The temperatures in the PLA slab are below 80 °C, but a more significant variation in its thickness is noticed.



a

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Fig. 6 – Temperature profiles after 500 seconds: a) perspective view in the cooling pipes (line) and in the mold (surface); b) frontal view of the cooling pipes (line) and the mold (surface).

This temperature gradient is more evident than in Fig. 4 and its nonuniformity along the “x” direction clearly appears. This may be caused by the fact that the PLA slab is in contact with colder surfaces, mainly in the regions where cooling water enters.

CONCLUSIONS

The simulation results indicated that during cooling the temperature profile varies in the PLA slab, and the temperature gradients are not uniformly distributed on the surface. These gradients may lead to defects in the final product. Nevertheless, according to simulation results, the values of these gradients are not very high and consequently this classical cooling system proves to be adequate for simple geometry of the PLA products.

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