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EFFECT OF COOLING SYSTEM ON THE POLYMER TEMPERATURE AND SOLIDIFICATION DURING INJECTION MOLDING

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ABSTRACT

Cooling system design is of great importance for plastic products industry by injection molding because it is crucial not only to reduce molding cycle time but also it significantly affects the productivity and quality of the final product. A numerical modeling for a T-mold plastic part having four cooling channels is performed. A cyclic transient cooling analysis using a finite volume approach is carried out. The objective of the mold cooling study is to determine the temperature profile along the cavity wall to improve the cooling system design. The effect of cooling channels form and the effect their location on the temperature
distribution of the mold and the solidification degree of polymer are studied. To improve the productivity of the process, the cooling time should be minimized and at the same time a homogeneous cooling should be necessary for the quality of the product. The results indicate that the cooling system which leads to minimum cooling time is not achieving uniform cooling throughout the mould.

Key words: Polymer; solidification; injection molding; cooling system.

NOMENCLATURE

\( C_p \)  Specific heat at constant pressure, J/kg.K
\( f_s \)  Solid fraction
\( h \)  Heat transfer coefficient, W/m\(^2\).K
\( K \)  Number of the internal iterations
\( L \)  Latent heat of fusion, J/kg
\( n \)  Number of the external iterations
\( N \)  Normal direction
\( S_c \)  Source term
\( T \)  Temperature, K
\( t \)  Time, s

Greek symbols
Thermal conductivity, \( W/m.K \)

\( \rho \) Density, \( \text{kg/m}^3 \)

\( \Gamma_1 \) Interior surface of the cooling channels

\( \Gamma_2 \) Exterior surface of the mold

Subscripts

- \( a \) Ambient air
- \( c \) Cooling fluid
- \( f \) Phase change

1. INTRODUCTION

Plastic industry is one of the world’s fastest growing industries, ranked as one of the few billion-dollar industries. Demand for injection molded parts continues to increase every year because plastic injection molding process is well known as the most efficient manufacturing techniques for economically producing of precision plastic parts with various shapes and complex geometry at low cost [1]. The plastic injection molding process is a cyclic process where polymer is injected into a mould cavity, and solidifies to form a plastic part. There are three significant stages in each cycle. The first stage is filling the cavity with melt hot polymer at an injection temperature (filling and post-filling stage). It is followed by taking away the heat of the polymer to the cooling channels (cooling stage), finally the solidified part is ejected (ejection stage). The cooling stage is of the greatest importance because it significantly affects the productivity and the quality of the final
product. It is well known that more than seventy percent of the cycle time in the injection molding process is spent in cooling the hot polymer melt sufficiently so that the part can be ejected without any significant deformation [2]. An efficient cooling system design of the cooling channels aiming at reducing cycle time must minimize such undesired defects as sink marks, differential shrinkage, thermal residual stress built-up and part warpage. During the post-filling and cooling stages of injection molding, hot molten polymer touches the cold mold wall, and a solid layer forms on the wall. As the material cools down, the solid skin begins to grow with increasing time as the cooling continues until the entire material solidifies. Over the years, many studies on the problem of the optimization of the cooling system layout in injection molding and phase change of molding process have been made by various researchers and ones which focused intensity on these topics and will used in our system design and validations are [3-6]. The main purpose of this paper is to study the effect of the cooling channels position and its cross section shape on the temperature distribution of the mold and polymer, therefore, their effect on the solidification degree of that polymer. A fully transient mold cooling analysis is performed using the finite volume method for a T-shape plastic mold with similar dimensions to [5], as shown in figure 1. Different cooling channels positions and forms are studied.

2. MATHEMATICAL MODEL

The heat of the molten polymer is taken away by forced convection to the coolant moving through the cooling channels and by natural convection to the air around the exterior mold surface. The coolant is flowing through the channels at a given flow rate and
a given temperature which is considered constant throughout the length of the channel. In this work, time-dependent two-dimensional model is considered which consists of an entire computational domain of the cavity, mold and cooling channel surfaces. The cyclic transient temperature distribution of the mold and polymer T-shape can be obtained by solving the transient energy equation.

\[
\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) \quad (1)
\]

In order to take into account the solidification, a source term is added to the energy equation corresponding to heat absorption or heat release [7], which takes in consideration the absorption or the dissipation of the heat through phase change process. This technique is applied on fixed nodes and the energy equation in this case is represented as follow:

\[
\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (\lambda \nabla T) + S_c \quad (2)
\]

And the source term \( S_c \) is represented by:

\[
S_c = \rho L_f \frac{\partial f_s}{\partial t} \quad (3)
\]

Where \( f_s(T) = 0.0 \) at \( T > T_f \), (full liquid region) \( 0 < f_s < 1 \), at \( T = T_f \) (isothermal phase change region) and, \( f_s(T) = 1 \) at \( T < T_f \) (full solid region).
On the whole domain, the following boundary conditions are applied

\[- \lambda_1 \frac{\partial T}{\partial N} = h_v (T - T_v) \quad \in \Gamma_1 \quad \text{and,} \quad - \lambda_2 \frac{\partial T}{\partial N} = h_a (T - T_a) \quad \in \Gamma_2 \]  \hspace{1cm} (4)

3. NUMERICAL SOLUTION

The numerical solution of the mathematical model governing the behavior of the physical system is computed by finite volume method. The equations are solved by an implicit treatment for the different terms of the equations system. When we take into consideration the solidification effect, the energy equation is solved with a fixed point algorithm for the solid fraction. For each iteration of that fixed point, we use discretization with time hybrid explicit/implicit technique already validated in previous studies by Vincent [8], and Le Bot [9] that is based on the technique «New Source» of Voller [10]. This method proposes to maintain the nodes where phase change occurs to the melting temperature. This solution is repeated until the convergence of the temperature with the source term equals to the latent heat. The source term is discretized by:

\[ S_e = \rho L_f \frac{\partial f_s}{\partial t} = \rho L_f \frac{f_s^{n+1} - f_s^n}{\Delta t} \]  \hspace{1cm} (5)

The solid fraction which is function of the temperature is linearized as:
\[ f_s^{n+\frac{k+1}{K}} = f_s^{n+\frac{k}{K}} + \left( \frac{dF}{dT} \right)^{n+\frac{k}{K}} (T^{n+\frac{k+1}{K}} - T^{n+\frac{k}{K}}) \]  

(6)

Then, we force the temperature to tend to the melting temperature where the source term is not null by updating the source term:

\[ S_{c}^{k+1} = S_{c}^{k} + \frac{\rho c_p (T - T_f)}{\Delta t} \]  

(7)

The energy equation is discretized as follow:

\[ \left( \frac{\rho c_p}{\Delta t} - \frac{\rho L_f}{\Delta t} \left( \frac{dF}{dT} \right)^{n+\frac{k}{K}} T^{n+\frac{k}{K}} \right) + \nabla \cdot \left( \lambda \nabla T \right)^{n+\frac{k+1}{K}} = \frac{\rho L_f}{\Delta t} \left( f_s^{n+\frac{k+1}{K}} - f_s^n \right) - \frac{\rho L_f}{\Delta t} \left( \frac{dF}{dT} \right)^{n+\frac{k+1}{K}} T_f^n + \frac{\rho c_p}{\Delta t} T^n \]  

(8)

With:

\[ \frac{dF}{dT} \rightarrow -\infty \text{ if } 0 < f_s^{n+\frac{k}{K}} < 1 \text{ and } \frac{dF}{dT} = 0 \text{ if } f_s^{n+\frac{k}{K}} = 0 \text{ or } 1 \]  

(9)

This process allows differentiating the temperature field and solid fraction calculated at the same instant and the linear system is solved by central discretization method [11]. For each internal iteration, the resolution of that equation provides \( f_s^{n+\frac{k+1}{K}} \) and \( T^{n+\frac{k+1}{K}} \). The convergence is achieved when the criteria of the solid fraction and temperature are verified by:
Further details on the numerical model and its validation are presented in [9].

4. RESULTS AND DISCUSSION

A full two dimensional time-dependent mold cooling analysis in injection molding is carried out for a plate mould model with T-shape plastic mold and four cooling channels as indicated in Fig. 1. Due to the symmetry, half of the mold is modeled and analyzed. All the cooling channels have the same size and they have diameter of 10-mm each in case of circular channels. The cooling operating parameters and the material properties are listed in tables 1, and 2 respectively and they are considered constant during all numerical results [5,7]. Each numerical cycle consists of two stages, cooling stage where the cavity is filled with hot polymer initially at polymer injected temperature, the ejection stage where the cavity is filled with air initially at ambient temperature. Figures 3, and 4 show the cyclic transient variations of the mould temperature with time for 16 seconds mold cooling time at locations; (P1,P2,P3,P4) beside the mould walls and P5 to P7 inside the mould walls respectively (Fig.1) and that in case of applied the solidification and without applied solidification. They are simulated for the first 30 cycles in case of circular cooling channels position (A5, D3) as shown in Fig. 2. We find that, the simulated results are in good agreement with the transient characteristic of the cyclic mold temperature variations described in [5]. It is found that there is a slightly difference in temperatures values
between the two results, thus due to the difference in numerical method used and the accuracy in the numerical calculations. The figures show that, the relatively temperature fluctuation is largest near the cavity surface and diminishes away from the cavity surface. We find that the maximum amplitude of temperature fluctuation during the steady cycle can reach 10 °C without applying solidification and 15 °C in case of applying the solidification.

4.1 Effect of cooling channels form

An efficient cooling system design providing uniform temperature distribution throughout the entire part during the cooling process should ensure product quality by preventing differential shrinkage, internal stresses, and mould release problems. It also should reduce time of cooling and accelerate the solidification process of the product to augment the productivity of the molding process. To demonstrate the influence of the cooling channels form on the temperature distribution throughout the mould and solidification process of the product, we proposed three different cross sectional forms of the cooling channels, circular, square, rectangular1 with long to width ratio of 0.5 and rectangular2 with width to long ratio of 0.25. Two cases are studied; first case, all the cooling channels have the same cross sectional area, and the second case, they have the same perimeter. The comparison is carried out for the same cooling channels position (A5, D3).
Figure 5 shows the solidification percent (calculated numerically as the summation of the solid fraction of each element multiplied by the area of that element to total area of the product) for different forms with different cooling time. The figure indicates that the effect of cooling channels form on the cooling rate decreases with increasing the cooling time. It also shows that the cooling channel form rectangle2 has the maximum solidification percent for case1, and in case 2 the changing of the cooling channels form has not a sensible effect on the solidification percent. The same results can be obtained when we compared the solidification in the product and the temperature distribution though the mould for different forms with the same cross sectional area at the end of the cooling stage for cooling time 24 second for cooling cycle 25, as shown in Fig. 6 and Fig.7 respectively. The results indicate that the cooling process is improved as the cooling channels tend to take the form of the product.

4.2 Effect of cooling channels position

To investigate the effect of the cooling channels position, we divided the proposed positions into four groups, group A, and B for different positions of the bottom cooling channel, with a fixed position of the top cooling channel, and with vice versa for group C, and D for the same cooling channel form (circular) as illustrated in Fig.2.

Figure 8 represents the effect of different cooling channel positions on the of solidification percent at the end of 25th cooling cycle for groups A, B (lower cooling channel effect), C, and D (upper cooling channel effect) with cooling time. It indicates that
for lower cooling channel position effect, the cooling rate increases and hence the solidification percent of the polymer increases as the cooling channel approaches the polymer in the vertical direction (position B has solidification percent greater than position A, and with the same position C and D). The figure shows also the most efficient cooling rate is obtained as the cooling channel takes the position between 20% and 50% through the product length for the horizontal direction (between positions B2, and B5 or positions A2 and A5 which have the maximum solidification percent). When we compare the solidification percent for different locations of the upper position C and D, we find that as the channel approaches to the product in the horizontal direction the solidification percent increases, and the cooling rate increase rapidly compared with the effect of lower position. We notice that, the effect of the cooling channel position on the temperature distribution and solidification decreases as the cooling time augments to higher value and its effect on the cooling rate of the product is not the same for different positions.

The solidification degree distribution through the product at the end of cooling stage at the end of cooling time 24 seconds and 25th cooling cycle for different locations of cooling channel is shown in Fig.9, and the temperature distribution throughout the mould and the polymer at the same instant for different cooling channels position is shown in Fig. 10. When we examine the solidification degree of the product and the temperature distribution throughout the mold for different positions, we find that as the cooling channel position moves toward the products, the homogeneity of the temperature distribution throughout the polymer and the mold during the solidification process decrease for example positions (B2, D3) and (B2,C3). The figure indicates that as the channel approaches the product in the
horizontal direction and vertical direction, the temperature distribution throughout the polymer divided into two regions during the cooling process (B7, D3), (B2, D3), (C5, B2), (C3, B2) and thus has the same effect on the solidification process. These two areas of the temperature distribution and that different cooling rate through the cooling process lead to different severe warpage and thermal residual stress in the final product which affect on the final product quality.

5. CONCLUSION

The variation of the temperature of the mould through a number of molding cycles is carried out. The simulated results are in good agreement with the transient characteristic of the cyclic mold temperature variations described in [5] and It is found that there is a slightly difference in temperatures values between the simulated results and those described in [5]. The effect of cooling channels form and the effect of its position on the temperatures distribution throughout the polymer and the solidification of the product are studied. The results indicate that as the cooling channels take the form of the product, the cooling rate is improved. The position of cooling channels has a great effect on the cooling process and temperature distribution through the mould and the polymer. The results show that the cooling system layout which performs minimum cooling time not necessary achieves optimum temperature distribution throughout the product, and the system layout must be optimized to achieve the both goals.
REFERENCES


Cooling operating parameter | Coolant fluid temperature | 30 °C | Ambient air temperature | 30 °C |
---|---|---|---|---|
Polymer injected temperature | 220 °C | Heat transfer coefficient of ambient air | 77 W/m².K |
Temperature of fusion of polymer | 110 °C | Heat transfer coefficient inside cooling channel | 3650 W/m².K |
Latent heat | 115 kJ/kg | Mold opening time | 4s |

Table 1: Cooling operating parameters
<table>
<thead>
<tr>
<th>Material</th>
<th>Density, kg/m$^3$</th>
<th>Specific heat, J/kg.K</th>
<th>Conductivity, W/m.K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mould</td>
<td>7670</td>
<td>426</td>
<td>36.5</td>
</tr>
<tr>
<td>Polymer</td>
<td>938</td>
<td>1800</td>
<td>0.25</td>
</tr>
<tr>
<td>Air</td>
<td>1.17</td>
<td>1006</td>
<td>0.0263</td>
</tr>
</tbody>
</table>

Table 2: Material properties
Fig. 1 Mold structure with a T-shape product and four cooling channels (Dim. In m).

Fig. 2 Different cooling channels positions (Dim. In m).
Fig. 3 Temperature history of the first 30 cycles at locations P1 to P4 (a) without solidification (b) with solidification.

Fig. 4 Temperature history of the first 30 cycles at locations P5 to P7 (a) without solidification (b) with solidification.
Fig. 5 Changing the solidification percent of the polymer part with cooling time for different cooling channel forms.

Fig. 6 Solidification percent distribution through the product for different cooling channels forms (a) rectangular2 and (b) circular having the same cross sectional area.
Fig. 7. Temperature distribution through the mould for different cooling channels forms (a) circular and (b) rectangular2 having the same cross sectional area.
Fig. 8. Changing the solidification percent of the polymer part with cooling time for different cooling channel positions (a) lower cooling channel positions A, and B and (b) upper cooling channel positions C, and D.
Fig. 9. Solidification percent distribution through the product for different cooling channels positions for cooling time 24 seconds and 25th cooling period (a) B7, D3 (b) B2, D3, (c) B2, C5, and (d) B2, C3.
Fig. 10. Temperature distribution through the mould for different cooling channels positions for cooling time 24 seconds and 25\textsuperscript{th} cooling period (a) B2, D3 and (b) B7, D3.