Model Investigation of the Cooling Error

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Abstract

Uniform cooling plays a large role in the production of high quality plastic parts. However, simulations to help with this task are often too expensive and complex to perform in the mold’s early design phases. The literature on this topic provides various equations dealing with this issue. The so-called ‘cooling error’ presents an example of the issues surrounding uniform cooling. Some strange experiences with the equation describing the cooling error revealed the need to validate it.

This paper examines the cooling error through thermal FEM simulations. The simulated results are then compared to those of the equation given in the literature. It turned out that it is necessary to re-evaluate the equation. Thereafter, the usefulness of the equation is analyzed with further thermal analysis.

Introduction

Setting up a mold for injection molding is a difficult job, and requires skills and knowledge of both the molded material as well as manufacturing technology. In order to assist with this task, Erich Schuermann [1] published in his dissertation many suggestions and equations. A lot of them are still quoted in today’s literature. [2] [3]

One of the equations is the ‘cooling error’, which is used to describe the cooling uniformity of plastic parts in a mold. To describe this the difference of the maximum and minimum heat flux of the cavity wall is divided by the average heat flux.

\[ j = \frac{\Delta q}{q} \]

To approximate this cooling error and avoid expensive testing only two coefficients are needed. The first is the Biot-number, a dimensionless constant describing the ratio of heat conduction and surface heat transfer. The second is the ratio of the distance between the cooling channels “b” and the distance of the cooling channel to the cavity wall “a”.

\[ Bi = \frac{\alpha \cdot d_{ck}}{\lambda} \]

\[ j = 2.4 \cdot Bi^{0.22} \cdot \left( \frac{b}{a} \right)^{2.8} \ln \left( \frac{b}{a} \right) \]

According to [1] the cooling error should be in a range of ≤ 5% for semi-crystalline polymers and ≤ 10% for amorphous materials [1]. This equation helps with the set-up of the cooling channels in the mold, and additionally takes into account the influence of the different mold materials or geometry changes.

The goal of this paper is to investigate the usage of the equation as well as its meaning for the conception phase of the mold. To achieve this, the predictions of this equation will be compared with the results of simple thermal simulations.

Simulation Set-up and Procedure

To investigate Schuermann’s equation, a thermal simulation with Ansys 17.2 ® similar to the experiments he described in his dissertation was set up. Only one stripe of the cavity with a single cooling channel was simulated. As in the original experiments, the cavity wall temperature was constant and set to 100°C. The cooling channel had a constant convection of 0.01 W/mm²·K, with a temperature of 80°C. The mold material was set as structural steel from the Ansys material database, and is listed in Table 1. The figure of the simplified set up is shown in the appendix.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [kg/m³]</th>
<th>Specific Heat Capacity [J/(kg·K)]</th>
<th>Isotropic Heat Conductivity [W/m·K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural steel</td>
<td>7872</td>
<td>481</td>
<td>45</td>
</tr>
<tr>
<td>Polymide</td>
<td>1400</td>
<td>1150</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 1: Material data

The first results of the simulation show the predicted heat flux distribution displayed in Figure 1, with the highest heat transfer directly underneath the cooling channel. The heat distribution decreased with distance to the channel. If we are looking at the heat flux distribution on the cavity wall, we can see a similar progression as in Schuermann’s
original investigation. Therefore, the simulation should be valid for further investigation.

In the following figure, the results of the FEM analyses are compared to the those of the equation. As an example, a b/a ratio of 1.75 is illustrated with a variation of the Biot-number.

Although we see a similar curve progression, the equation clearly underestimates the cooling error calculated in the simulation. Within other investigations of different Biot-Number and b/a ratio combinations an overestimation of the cooling error was observed. Figure 4 shows the equation’s relative error compared to the FEA results.

The figure shows that the relative error is largest within a small b/a ratio ≤ 1. In addition, its value varies greatly. As the ratio increases between 1.5 – 2, the error is rather small but then increases with a b/a ratio ≥ 3.
Nonlinear Regression Analyses

The results of the simulated cooling error and the equation show a similar curve progression but the range between their values is large. To fit the new collected data to the equation, a nonlinear regression analyses with Minitab 17® was executed.

Due to the similar curve progression, the original equation was used to find new coefficients. Due to the larger difference in the range of small cooling errors, this data was biased to better fit the curve in this area. Additionally, a simplification of the original equation was investigated. Equation (4) is the original equation but with the new factors. (5) reflects the simplified version of the original equation.

\[
 j = 2.6832 \cdot B^i 0.3625 \left( \frac{b}{a} \right)^2 \ln \left( \frac{b}{a} \right) 
\]

(4)

\[
 j = 1.3662 \cdot B^i 0.35568 \left( \frac{b}{a} \right)^{2.83818} 
\]

(5)

Average relative error

<table>
<thead>
<tr>
<th>Equation Type</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original equation</td>
<td>1.25</td>
</tr>
<tr>
<td>New parameter equation</td>
<td>1.4</td>
</tr>
<tr>
<td>Simplified equation</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2: Average relative error of different cooling error equations

In Table 2, the average relative error of the new equations are compared to the original equation. The new parameter of the original equation cannot lead to a decrease of the average relative error. However, the simplified equation is able to achieve a decrease of approximately 50% of the average relative error.

Transient Thermal Analysis

The steady state thermal analysis leads to a re-evaluation of the equation. In order to evaluate the simplification of the steady state analysis, a transient simulation was set up.

The transient simulation allows us to investigate several cycles of the mold as well as the cooling of a polymer part. The part, a simple plate with a thickness of 1.5 mm, was added to the FE-model. The plate’s material is a Polyimide, and the material characteristics can be seen in Table 1. A simplification of the simulation was required in order to reduce the expense of the work. The injection of the plastic melt, as well as the back pressure, could not be displayed. Instead, on each cycle the temperature of the plastic part was set to the melt temperature of 240°C for 0.1 seconds. Afterwards the part is assumed to cool down for the remaining cycle time, which was set to 7.5 seconds. To achieve a higher heat flux, the cooling channel’s temperature was set to 30°C. The convection was set to 0.01 W/mm², which results in a Biot-number of 2.2. The b/a ratio was set to 4. In total 19 cycles were simulated, and the cooling error calculated 0.2 seconds after the polymer was applied to the melt temperature. The results of the cooling error can be viewed in Figure 5, which displays the increase of the cooling error over the number of cycles. Within the last 5 cycles, only a small increase in the cooling error was visible, and we can almost originate a steady state at this point.

If the last simulated cycle displays the steady state, and we compare the cooling error with the same settings in a steady state simulations, the cooling error is approximately 87% compared to the 9% of transient simulation. This is a major difference.

In the following step the temperature distribution of the last cycle was examined. A temperature distribution of maximum 15°C could be seen, and thus the wall temperature could not be considered constant. Instead of the constant temperature, the temperature distribution was applied on the cavity wall.

As a result, the cooling error decreased from 87% to 42%. In addition, the distribution of the heat flux changed in this simulation. In the previous simulation, the highest heat flux appeared directly underneath the cooling channel, but as a result of the temperature distribution it moves closer to the outside wall. The following figure displays this development.

Figure 5: Increase of cooling error with number of cycles

Figure 6: Total heat flux distribution on the cavity wall
Conclusion

Although the simulation was set up similar to suggestions in the literature, the predicted results of the equation could not be verified. With a nonlinear regression analysis, a simplified equation was found with a roughly 50% decrease of the average relative error. Still, regions of low and high cooling errors could not be displayed correctly.

The results of the transient analysis show that the cooling error increases with every cycle and then approximates to an almost steady state. The maximum cooling error of the cycle shows a significantly lower value than the prediction of the steady state simulations.

Applying a temperate distribution instead of a constant temperature to the cavity wall lead to a reduction of the cooling error. The reason for this could be found in the lower temperature and resultant reduction of the heat flux underneath the cooling channel. The reduction of the cooling error is still higher than the results from the transient simulations.

Discussion

The transient calculation showed that the temperature variation should be taken into account while calculating the cooling error. Since the heat flux is altered in this situation, the cooling error is influenced. The large difference between the transient and steady state simulation raises interesting questions. Although the transient simulations should display the reality better than the steady state simulations, the simplifications made could lead to a distortion of the results. The examination of the heat flux at the contact area between the mold and the part is an example of this. In the injection molding process, the injected polymer freezes into a thin layer right after contact with the mold. In the set-up simulation, this could not be considered.

The temperature of the part was set to 240°C at the beginning of each cycle. Measuring the heat flux at this area could distort the results, as the small frozen layer of polymer acts as an isolator and could therefore change the heat flux. Furthermore, the packing phase adds additional heat into the mold cavity, whose influence is also not considered. To investigate this in more detail, the injection of the polymer should be considered in future simulations.

This leads to the final question: is the definition of the cooling error even suitable? Does the temperature variance and the heat flux distribution not have different effects on the part’s quality? Should the part's cooling speed variation as well as the temperature difference of the mold not be the center of the investigation?

Until the this questions are solved, and with the results of this paper in mind, the equation’s usage cannot be recommended. If, however, one could predict the cooling error with the necessary accuracy, the prediction would indeed be a helpful tool during the set-up of a mold.

References

Appendix

Figure 7: Set-up of the steady state simulation

Figure 8: Set-up of the transient thermal simulation