



## The effect of limescale on heat transfer in injection molding



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### ABSTRACT

With the development of rapid prototyping technologies, injection mold inserts with conformal cooling systems can be manufactured from metal powder by direct metal laser sintering (DMLS). The conformal cooling channels are placed along the geometry of the injection molded product, thus they can extract more heat, and heat removal is more uniform than in the case of conventional cooling systems. But even the most efficient cooling circuits start to wear out, corrosion and limescale depositions precipitate on the wall of the cooling channel, which impede heat transfer from the mold to the coolant. The effect of the depositions cannot be neglected and the modeling of the impact on heat transfer is difficult. We developed a model to investigate the effect of limescale that formed on the wall of the cooling circuit. The thermal properties of the limescale are required for the simulation, therefore they were measured. We concluded that 2 mm thick limescale impedes heat removal so much that the more efficient conformal cooling system can only extract as much heat as the less efficient conventional system.

### 1. Introduction

Injection molding has seen rapid progress in the past decades and now it is one of the most important polymer processing technologies. The cooling time of the part is a significant phase of the injection molding cycle. In the case of materials with high processing temperature, large-volume or complicated geometry products, cooling time can be more than half of the whole cycle. With such products a reduction in cooling time considerably improves productivity. One of the best ways to achieve this is to use mold inserts with conformal cooling. As opposed to a conventional cooling system, this system follows the geometry of the product, therefore it can extract more heat and heat extraction is also more uniform, which results in a reduction of cycle time and an improvement in product quality [1–7]. Conformal cooling channels are widely used in the production of plastic parts because of their benefits [8–9]. In addition, the use of conformal cooling channels makes it possible to tailor the cooling rate, so in the case of a semi-crystalline material, the crystallinity of the injection molded product can be set without fillers [10–11].

Mostly water is used to cool the inserts, without any limescale or corrosion inhibition. The thermal conductivity of limescale deposition is two orders of magnitude lower than that of tool steel, which hinders heat transfer from the mold to the coolant. The effect of limescale deposition is more often investigated in the case of heat exchangers, only a few articles focus on injection molds. Pezzin et al. [12] investigated limescale in turbulent flow heat exchangers and concluded that even

2 mm of limescale increases energy consumption by 12%. They approximated the thermal conductivity value of the limescale to be around 2.2 W/(mK), but did not measure its exact value. The effect of limescale and rust in injection molding was analyzed by Novoplan GmbH [13]. The investigations were done with the Moldex 3D injection molding simulation software. They concluded that in the case of their box-shaped product 1 mm of rust increases mold surface temperature by 20 °C and warpage by 0.4 mm. 1 mm of limescale has a bigger impact on temperature and warpage; it doubles the values caused by rust. Furthermore, the efficiency of the cooling circuits drops by 6%. The authors did not specify the thermal conductivity of the depositions in their work and did not give information about the method of measuring thermal conductivity.

Injection molding simulations are used to make proper cooling layouts and it is even more important to use computer calculations for conformal cooling systems. The accuracy of the results is greatly influenced by the precision of modeling, boundary conditions and the calculation algorithms.

More and more articles focus on the development of injection molding simulations to get faster and more accurate results. Zhang et al. [14] developed a novel boundary element method based cooling simulation method for steady-state cooling. The analytical solution of the part temperature was introduced into the boundary element method, so the RAM size required for the calculations was reduced on average by 93% and calculation time was shortened by one order of magnitude. Liu and Gehde [15] analyzed the influence of the heat transfer coefficient

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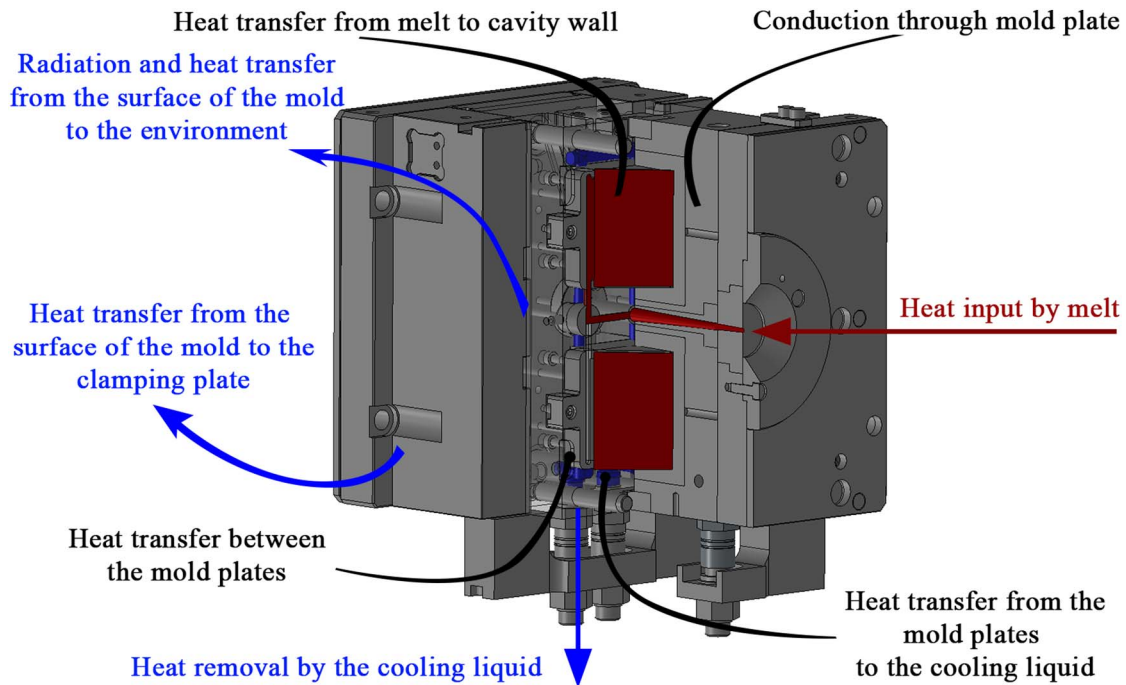


Fig. 1. Total heat flow in the mold.

between the polymer and the cavity wall on cooling and crystallinity. They found that melt temperature and surface roughness have an important role in determining the HTC. A difference between the frozen percentages calculated by the observed and preset HTC values were reported, and the HTC also influenced relative crystallinity. Kovács et al. [16] determined the influence of the thermal parameters of the prototype mold insert based on the measured temperature results. It was concluded that numerical calculations can be used to determine thermal and other parameters of rapid-tooled mold inserts, but the calculated results are only approximations, because the numerical algorithm cannot handle the temperature and pressure dependence of the thermal properties of prototype molds. Urquhart and Brown [17] investigated the effects of uncertainty in heat transfer data using numerical analysis. They concluded that uncertainties in the thermal conductivity of the mold and the heat transfer coefficient between the mold and melt only have a minor effect on the time to reach ejection temperature compared to the thermal conductivity of the polymer melt. Only a change of about 10% in mold thermal conductivity can affect the temperature results significantly. The effect of the heat transfer coefficient is even smaller, a significant change in the results can only be observed in the case of thin-walled parts (maximum thickness 0.5 mm) and with a change of two orders of magnitude in the heat transfer coefficient.

## 2. Heat transfer equations

Nomenclature			
A	cross section, m <sup>2</sup>	α	heat transfer coefficient, Wm <sup>-2</sup> K <sup>-1</sup>
g	gravitational acceleration, m s <sup>-2</sup>	β	polymer expansivity, K <sup>-1</sup>
p	pressure, Pa	δ	thickness, m
c <sub>p</sub>	specific heat, Jkg <sup>-1</sup> K <sup>-1</sup>	ε	emissivity, -
t	time, s	ρ	density, kg m <sup>-3</sup>
ΔT	temperature difference, °C	λ	thermal conductivity,

v	velocity, ms <sup>-1</sup>	Wm <sup>-1</sup> K <sup>-1</sup>
R	heat resistance, KW <sup>-1</sup>	σ <sub>0</sub> Stefan-Boltzmann constant, Wm <sup>-2</sup> K <sup>-4</sup>
R <sub>λ</sub>	heat resistance caused by conduction, KW <sup>-1</sup>	R <sub>α</sub> heat resistance caused by heat transfer, KW <sup>-1</sup>
λ <sub>limescale</sub>	thermal conductivity of limescale, Wm <sup>-1</sup> K <sup>-1</sup>	r <sub>1</sub> inner diameter of the limescale deposition, m
α <sub>coolant-lime-scale</sub>	heat transfer coefficient between coolant and limescale, Wm <sup>-2</sup> K <sup>-1</sup>	r <sub>2</sub> outer diameter of the limescale deposition, m
		L length of the limescale deposition, m

From a thermal aspect, injection molding starts with the injection phase, where the melt is injected into the tempered cavity at a high speed until the cavity is fully filled. The melt starts to transmit energy to the mold right after it touches the wall of the mold. In the upcoming packing phase some more melt is forced into the cavity, so more heat is taken into the mold. The pressure drops during the cooling stage until it reaches atmospheric pressure, and because of volumetric shrinkage, air gaps are formed at several places between the cavity wall and the injection molded part. The intensity of heat removal is the highest in the injection phase, because cavity pressure and the temperature difference between the melt near the wall and the cavity wall are the highest. The calculation of melt flow and temperature distribution can be executed by Navier-Stoke's momentum (1), continuity (2) and energy (3) conservation equations [15,18]:

$$\rho \cdot \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \nabla (\eta \cdot (\nabla \mathbf{v} + (\nabla \mathbf{v})^T)) - \frac{2}{3} \eta \cdot \nabla (\nabla \mathbf{v}) + \rho \cdot \mathbf{g}, \tag{1}$$

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{v}) = 0, \tag{2}$$

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