BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF POLYMER ENGINEERING

ANALYZING THE HEAT TRANSFER PROPERTIES OF INJECTION MOLDS AND DEVELOPING THE MEASUREMENT METHODS OF THESE PROPERTIES

THESIS BOOK OF PHD DISSERTATION

MADE BY:
BÉLA ZINK
MECHANICAL ENGINEER

SUPERVISOR:
DR. JÓZSEF GÁBOR KOVÁCS

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The review and the defense report of the doctoral dissertation can be viewed at the Dean's Office of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics

1. Introduction

Today, the plastic industry is one of the most important industries worldwide. In 2016, the production of plastics in the world exceeded 322 million tons. One of the most important plastic processing technologies is injection molding; nearly one-third of plastic products are manufactured with this technology. Willert patented the reciprocating-screw injection molding plastication unit in 1956, which is the basis of modern machines as well. This invention started the dynamic development of injection molding technology. By now this technology has become very accurate and economical, and can produce excellent product quality. Several new procedures supporting injection molding have been developed, such as injection molding simulation and rapid tooling (RT). The use of these methods further improves efficiency.

During the injection molding cycle, complex thermal processes take place in the mold, which determine the thermal load on the mold, the quality of the product, and the lifetime of the mold, as well. Heat input into the mold starts with the inflow of melt. As soon as the melt gets into contact with the mold, heat removal form the melt starts. Heat is removed by the coolant, the environment and certain parts of the mold, in the form of heat transfer, conduction and radiation. Of these, heat transfer and heat conduction are dominant in injection molding. Controlled heat removal lasts until mold opening; after ejection, the injection molded product cools to ambient temperature. The thermal processes in the mold can be calculated with numerical procedures, with approximations and certain neglections, thanks to the ever-increasing computing power of modern computers.

The programs using numerical approximations started to be developed at the end of the 1970s. Initially, the cost and limited computing power of the hardware were a major challenge. With today's modern machines, injection molding simulation programs can help analyze and avoid numerous mold design problems. Complex thermal processes, however, can still only be handled with neglections and approximations. These thermal results are used as input parameters for further calculations and the neglections in the thermal processes often make it impossible to eliminate complex injection molding defects with the help of numerical calculations. New materials, increasingly used in injection molding (copper, aluminum, epoxy-acrylate-based resins etc.), have different thermal parameters than conventional mold materials and complex cooling circuit layouts (conformal cooling systems) make thermal calculations more complicated. In these cases, inaccurate initial and boundary conditions can produce greater calculation errors.

Injection mold inserts manufactured by rapid prototyping make the production of small-series products faster and more cost-effective. With these technologies, the mold is built in an additive way, layer-by-layer, and the whole process is computer-controlled. Rapid prototyping makes new tooling methods possible; mold and cooling circuit geometries of any complexity can be manufactured with it. These polymer-based inserts, however, have considerably different thermal parameters than metal molds. The thermal conductivity of the mold material is several orders of magnitude worse than that of metals, therefore heat removal is slow, and the heat load on the mold surface in contact with the melt, and its immediate vicinity, is higher than in other parts of the mold insert.

The goal of my dissertation is to analyze the heat transfer processes of injection molds, and to develop measurement methods for these. I make the input parameters of numerical calculations used for injection molding (heat transfer coefficient and heat conductivity) more accurate, with special attention to the thermal parameters of polymer-based small-series molds. My further goal is to analyze the effect of mold materials and cooling circuit layouts on cooling efficiency and numerical calculations with injection molding and numerical procedures. I plan to use the measurement results to make the cooling analyses of simulation programs more accurate. In my dissertation I also model the limescale layer deposited in the cooling channels, measure the thermal parameters of the limescale and numerically calculate its effect on cooling efficiency.

2. The review and critical analysis of the literature

Additive technologies have made the small-series production of injection molded products economical. The greatest problem of small-series molds is their short lifetime. The material has inferior thermal conductivity, therefore it cannot remove the heat from mold parts that are in contact with the product, therefore their temperature rises above the glass transition temperature and the mechanical properties of the mold material deteriorate considerably. For heat to be conducted fast from small-series molds, the thermal conductivity of the usually photopolymer-based mold materials needs to be increased. Several researchers have focused on the improvement of the mold materials of small-series molds, but the most important aspect has been the improvement of mechanical properties. Mechanical properties can be improved by adding calcium phosphate, calcium bentonite, silicon carbide, carbon nanotubes etc. but also curing later. These authors have paid little attention to the improvement of the thermal conductivity of the mold materials and to cooling circuits. In most tests, instead of using cooling circuits, they increased the lifetime of the mold by increasing cycle time and reducing injection and holding pressure. They found that it is mostly the flexural load during the injection phase that destroys small-series injection molds. Reducing pressures and increasing cycle time, however, decrease the dimensional accuracy of the product but the authors did not investigate this.

Additive technologies can be used to produce large-series molds and they can have conformal cooling circuits, which can remove more heat from the product in a shorter time. Several authors have written about the advantages of conformal cooling circuits; they have found that conformal cooling provides a considerable advantage if the volume of the injection molded part is large, its geometry is complex or injection molding temperature is high. In these cases, the highest mold temperature was reduced by nearly 50%, temperature distribution was more even and cycle time decreased by 25%. Researchers have also focused on the numerical checking of conformal cooling systems but in most cases, they applied considerable neglections when calculating flow in the cooling circuits. When they measured mold temperatures with a thermal imaging camera, they did not determine the reflection coefficient of the mold inserts, even though, without its accurate value, temperature cannot be measured accurately.

Simulation programs approximate heat transfer between the polymer and the mold wall. Heat transfer is highest at injection, it gets lower during the holding phase and even lower during cooling, but the exact heat transfer coefficients are not known. In the holding and cooling phase, pressure decreases until locally it is reduced to atmospheric pressure, the part separates from the mold wall and heat transfer decreases radically. Some researchers have researched this phenomenon, but the values obtained by them differ: the heat transfer coefficient varies between 500-6600 W/m^2K. They examined various measurement and calculation methods, and found that the sensitivity of the model based on surface and conduction thermal resistance is inadequate. The heat transfer coefficient may be determined with the progessive difference method; for this, initial values need to be measured, which can be performed with an infrared thermocouple.

Injection molding is suitable for the production of complex geometry plastic products economically and with high dimensional accuracy. The quality of the product is mostly determined by the holding and cooling phase; the cooling phase is the longest phase of the injection molding cycle. Therefore, the cooling phase is the most important technological phase from an economic and quality aspect. If a layer of limescale or corrosion forms, it impairs heat transfer and the efficiency of conformal cooling systems is also considerably impaired. Only a few papers have been written on this subject. The authors have found that a limescale layer of 1 mm thickness increases the maximum surface temperature of the part at ejection by 40 °C, which causes an additional 0.9 mm deformation compared to the same cooling circuit without limescale. Research has found that corrosion impairs quality and increases cycle time less. On the other hand, researchers did not determine the heat transfer coefficient of limescale or a layer of corrosion in any of the papers, and they did not analyze the factors affecting the formation of the deposits, either. Nor did they check the results of numerical calculations with thermal imaging camera or sensor measurements.

Based on the literature review, I set the following goals:

- Thermal analysis of photopolymer-based small-series molds, and analyzing the effect of cooling circuits on the lifetime of molds.
- Thermal analysis of conformal cooling circuits with a numerical method and measurements, and the comparison of the thermal processes of steel molds with conformal cooling and high thermal conductivity copper molds with conventional cooling. Analysis of the effect of surface quality and mold coating on thermal imaging camera measurement.
- Analysis of the thermal processes occurring between the polymer melt and mold wall, and developing a procedure and device for the measurement of the heat transfer coefficient.
- Determining the thermal parameters of limescale (thermal conductivity, density and specific heat) of different compositions. Analysis of the effect of deposits on heat transfer with a numerical method.

3. The materials and machines used for the tests

In the following chapters I present the equipment, materials and test methods.

3.1. Injection molding materials

I used Terluran GP35 ABS manufactured by Styrolution for the testing of mold inserts of various materials and cooling circuit geometries. ABS can be processed by injection molding. I used Tipplen H-145F polypropylene manufactured by MOL Petrolkémia Zrt. for the thermal analysis of small-series molds. I determined the heat transfer coefficient with specimens injection molded from Ineos PP 100-GA12, manufactured by INEOS Olefins & Polymers.

3.2. Mold materials

Large-series mold inserts used in the tests were made from 1.2311 (P20) (Böhler) and MaragingSteel1 (MS1) (EOS) steels, and Ampcoloy 940 and 88 (Ampcometal) copper alloy. Small-series mold inserts were made from two epoxy-based resins: Fullcure 720 (RGD720) (Stratasys) and Digital ABS Plus (RGD5160-DM) (Stratasys).

3.3. Mold design and insert designs

The mold has two cavities and the temperature of the moving side and the stationary side can be controlled separately (Fig. 1). The part is made up of two 2 mm thick sheets perpendicular to each other. On the core side, at the main edge, where the two sheets meet, heat accumulates due to the corner effect.

I examined four different cooling circuit layouts. The cooling circuits were designed based on the design aspects of conventional cooling circuits in each case. The first cooling circuit has a conventional layout, the cooling channels were drilled (*Conventional cooling circuit*) (Fig. 2/a). The diameter of the cooling channels is 8 mm because the injection molded part is 2 mm thick. Their center line is 13.2 mm from the surface on the cavity side and 12 mm from the surface in the core-side insert.

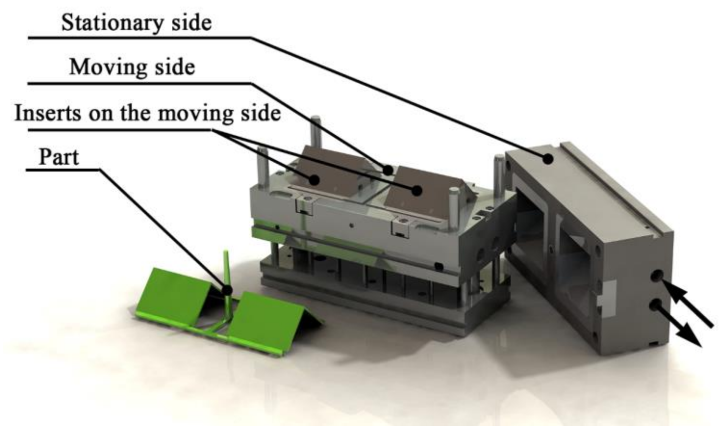
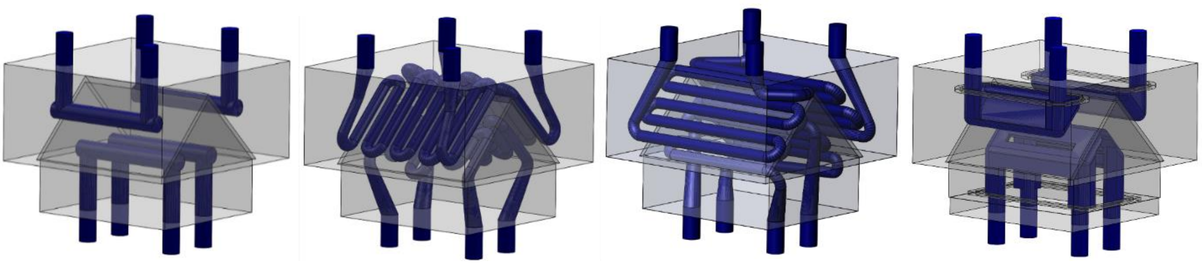


Fig. 1 The mold and the part manufactured with it

The second and third cooling circuits are conformal cooling circuits and were made by additive manufacturing technology. In these cooling circuits, the diameter of the cooling channels is smaller and they are nearer the injection molded part than in the case of the conventional layout. Heat removal is uniform because the channels follow the geometry of the part (Fig. 2/b and c). The diameter of the cooling circuits gradually decrease from 8 mm to 5 mm after they enter the insert, the distance of the cooling channels from the surface of the core side and the cavity side is 6.5 mm and the cooling channels are 8.5 mm from each other. The biggest difference between the two cooling circuits is the direction, layout and volume of the channels. In one of the layouts, the channels are perpendicular to the main edge of the core side (*Perpendicular conformal cooling circuit*) (Fig. 2/b), while in the other layout, the cooling channels are parallel to the main edge (*Parallel conformal cooling circuit*) (Fig. 2/c). The volume of the cooling channels in the case of the *Parallel cooling circuit* is 27% larger on the core side and 13% higher on the cavity side than in the case of the *Perpendicular cooling circuit*.

The cooling channels of the fourth mold insert are machined. The insert consists of two parts; the cooling circuits seen in Fig. 2/d are formed after the parts are assembled (*Cored cooling circuit*). The heat removal surfaces of the cooling circuits are 8 mm from the cavity surface in the inserts on both sides.



a) b) c) d)

Fig. 2 Conventional (a), perpendicular conformal (b), parallel conformal (c) and machined, cored (d) cooling circuits

3.4. Machines and measuring instruments

Injection molding machine

The specimens for the determination of the heat transfer coefficient were injection molded and the thermal measurements were performed on an Arburg 370S 700-290 injection molding machine.

Controlling the temperature of the molds

The temperature of the molds was controlled with a Wittmann Tempro Plus 90 temperature controller.

Differential Scanning Calorimetry

The specific heat of the materials was measured with a TA Instruments Q2000 Differential Scanning Calorimeter. I used a heat-cool-heat program in the 0-120 °C temperature range with a heating/cooling rate of 2 °C/min. The mass of the samples was between 15-20 mg in each case, and at the bottom of the sample holder the powdered sample was evenly distributed.

Dynamic Mechanical Analysis

The storage modulus and loss factor of Fullcure 720 and Digital ABS were measured with a TA Instruments DMA Q800 instrument. In the measurements, both materials were loaded with single side clamping and deformation excitation with an amplitude of 20 μm. Support length was 17.5 mm and heating rate was set to 1 °C/min. The tested temperature range was 0-100 °C in the case of Fullcure 720, and 0-160 °C in the case of Digital ABS. In each case three measurements were averaged.

Thermal imaging camera

The thermal camera measurements were performed with a Flir A325 SC thermal imaging camera.

Data acquisition module

I used an Ahlborn Almemo 8990-6-V5 data acquisition module and NiCr-Ni T190 thermowires in the determination of the thermal conductivity of the limescale samples and the thermal analysis of the small-series molds. Resolution was set to 0.1 °C, and sampling time was 0.3 s and 3 s.

Capillary plastometer

The standard melt flow index (MFI) was determined with a CEAST 7027.000 capillary plastometer according to the MSZ EN ISO 1133:2005 standard, at 200 °C and with a load of 2.16 kg.

Balance

An Ohaus Explorer analytical balance was used in the determination of the density of the limescale samples. The range of the balance is 0-110 g, and its accuracy is 0,0001 g.

Press

I determined the thermal conductivity of limescale on a Collin Pressplate 200E hydraulic press by heating the samples to 50 °C and 80 °C, at pressures of 60, 120, 180, 250, 300, 425, and 550 bar.

Universal testing machine

I determined the heat transfer coefficient on a Zwick Z250 testing machine at 11, 22, 44, 110 and 220 kN loads. The diameter of the specimen in the tests was ø75 mm, and its thickness was 2 mm.

Software

For the numerical calculations I used the 2015-2018 versions of Autodesk Moldflow Synergy, which contain the Computational Fluid Dynamics (CFD) algorithm used for finite element cooling calculations.

4. Summary

At the beginning of my dissertation, I briefly presented the more important definitions related to additive technologies, I covered thermal processes in small-series molds manufactured by additive technologies in detail, the failure of molds, and the materials that can be used to manufacture small-series molds. Then I compared conventional and conformal cooling circuit layouts, showed the advantages and design aspects of conformal cooling layouts. I also presented research and its results on determining the heat transfer coefficient between the polymer melt and the mold wall. Finally, I examined the effect of limescale and corrosion deposits on cooling efficiency.

I further developed the methods of the measurement and numerical calculation of thermal processes in injection molds. Numerical calculations usually neglect the pressure dependence of the heat transfer coefficient between the mold insert and the melt, and it causes considerable error. I developed a measurement method and measuring equipment to determine the heat transfer coefficient between the mold wall and the melt as a function of pressure and temperature. I pressed polypropylene specimens between two reference cylinders at pressures of 25, 50, 100, 250 and 500 bar, on a Zwick Z250 tensile tester. Based on the measurement results, I determined the heat transfer coefficient between the melt and the mold wall, and generated a formula which can be used to calculate the heat transfer coefficient as a function of pressure and temperature. I performed additional measurements to check the formula, and I proved that it is correct. I also performed error calculations to determine the quadratic relative error of the method.

The parameters describing heat transfer processes serve as input for numerical calculations and thus greatly affect calculation results. More and more special injection molding tooling solutions appear on the market, with which better quality products can be manufactured faster. Such solutions are the use of special, conformal cooling circuits and highly alloyed copper mold materials, this is why I used numerical methods and a thermal imaging camera to examine steel (*DMLS*) mold inserts with conformal cooling, steel (*P20*) mold inserts with conventional drilled cooling circuits and copper (*Ampcoloy*) mold inserts. I found that the direct thermal camera measurements of mold inserts of ε=0,5 emission coefficient manufactured with electrical discharge machining ($R_{a,average}$= 1,98) is inaccurate due to radiation in the environment, therefore accurate measurements require surface treatment. I determined from the numerical and thermal camera analysis of mold inserts that the highly alloyed copper mold insert removes heat more effectively and evenly from a simple corner geometry injection molded part, even with conventional cooling, than the *DMLS mold insert*. In the case of the *P20 mold insert,* I found a difference of almost 5 °C between the measured and calculated temperatures, which is probably due to the inaccurate initial and boundary conditions. I found that in the case of the *P20 mold insert,* modeling the joining gap between the stationary and moving half can reduce the difference between the measured and calculated values by 65%. The rest of the difference may be due to the surface roughness of the cavity surface and the cooling circuits, and to the fact that the temperature of the cooling liquid may be up to 2 °C warmer or cooler during the injection molding cycle than the value set in the simulations.

Conformal cooling can also be applied in the case of small-series injection molds manufactured with an additive technology; it can reduce the heat load and increase lifetime, therefore I performed thermal analysis on mold inserts made from FullCure 720 and Digital ABS Plus. I compared four molds: one had conventional cooling, another had no cooling and the other two had conformal cooling with different layouts. I found that there is no point in applying conventional cooling because the measured temperature values did not show a significant difference from those of the uncooled mold insert. Conformal cooling, on the other hand, significantly reduces the heat load of the insert; with conformal cooling, the time above the glass transition temperature can be reduced by 70% compared to no cooling or conventional cooling. The injection cycle of small-series plastic molds can be divided into three phases based on thermal aspects: in the first phase, heat transfer is dominant, and the temperature of the mold increases monotonously. In the second phase, when the surface temperature of the melt and the mold is roughly the same, heat conduction and heat removal by cooling are dominant. In the third phase, when the part has been ejected, it is mostly cooled by heat radiation and convection.

Limescale deposits in the cooling circuits inhibit heat removal, which impairs product quality and productivity. I proved the effect of limescale deposits in the case of a simple, corner geometry part. I measured the thermal parameters necessary for the calculations (average heat conductivity 1,37 W/(mK); average specific heat 800 J/kgK,) and density (2,33 g/cm^3). I found that a limescale layer of 2 mm thickness reduces the cooling efficiency of a conformal cooling circuit to the cooling performance of conventional cooling because most heat is removed by the cooling liquid. On the other hand, in the case of the high thermal conductivity copper mold, most heat is removed by thermal conduction, therefore, limescale does not impair heat removal considerably.

5. Theses

Thesis 1

I proved that the cooling efficiency of injection molds is mostly determined in the generally used cooling circuit diameter range by the layout of the cooling circuits, that is, the path of the cooling channels, the mold material and possible deposits.

I proved that in the case of simple geometry injection molded products, a high thermal conductivity alloyed copper mold insert can remove more heat in the same cycle time even with conventional, drilled cooling circuits than a Direct Metal Laser Sintered steel mold insert with conformal cooling.

I proved my thesis with numerical calculations and temperature measurements. I used injection molds made from Ampcoloy 940 copper, Böhler 1.2311 steel and MaragingSteel MS1 steel to injection mold parts from acrylonitrile butadiene styrene [1, 3, 4, 8, 10].

Thesis 2

I proved that if the thermal resistance of the joining gaps of mold inserts are taken into account, numerical calculations can be made more accurate in the case of molds with low-efficiency cooling circuits, where the role of heat transfer between mold parts involved in heat removal increases.

I proved my thesis with numerical calculations and temperature measurements using injection molds made from Ampcoloy 940 copper, Böhler 1.2311 steel and MaragingSteel MS1 steel to injection mold parts from acrylonitrile butadiene styrene [1, 3, 4, 8, 10].

Thesis 3

I made an equation which can describe how deposits forming in injection molds influence cooling efficiency:

$$H = H_0 \cdot \frac{{\lambda_l}^{C_3(\lambda_{sz})\cdot V_l + C_4}}{(\lambda_{sz} - \lambda_l)\cdot \left(C_5(\lambda_{sz})\cdot {V_l}^{C_6}\right)^{(C_3(\lambda_{sz})\cdot V_l + C_4)} + {\lambda_l}^{C_3(\lambda_{sz})\cdot V_l + C_4}}$$

where H_0 [%] is cooling efficiency when there is no deposition, λ_l [W/(mK)] and λ_{sz} [W/(mK)] are the thermal conductivity of the deposit and the mold, respectively, $C_3(\lambda_{sz})$ [1/m] and $C_5(\lambda_{sz})$ [1/m] are constants depending on the thermal conductivity of the injection mold, C_4 [-] and C_6 [-] are constants depending on the thickness of the deposit, and V_l [m] is the thickness of the deposit.

I proved my thesis by modeling deposits of 0,25, 0,5 and 1 mm thickness and no deposit, and a heat conductivity of 0, 0.1, 0.15, 0.25, 0.56, 1, 1.37 and 1.74 W/(mK), in the case of conventional and conformal cooling layouts [5].

Thesis 4

In the case epoxy acrylate-based prototype molds, I showed that the time the mold insert spends above the glass transition temperature can be reduced by up to 70 % with the use of conformal cooling, which increases the lifetime of the insert significantly. I also proved that in the case of epoxy acrylate-based injection molds, conventional cooling does not improve heat removal considerably compared to no cooling at all. I proved my thesis with RGD 720 and RGD 5160-DM epoxy acrylate-based mold inserts and measurements carried out with polypropylene [2, 6, 7].

Thesis 5

I elaborated a special method based on pressing, and the related evaluation theory with which the heat transfer coefficient between the polymer and the mold wall can be determined as a function of temperature difference and pressure in both melt and solid state.

I proved that the quadratic absolute error of the procedure I developed can be obtained with the following formula:

$$\frac{\delta\alpha}{\alpha} = \sqrt{\frac{\left(\delta\Delta T_{ref}\cdot\frac{\partial\alpha}{\partial\Delta T_{ref}}\right)^2 + \left(\delta\Delta T_{ref,felület}\cdot\frac{\partial\alpha}{\partial\Delta T_{ref,felület}}\right)^2 + \left(\delta\delta_{minta}\cdot\frac{\partial\alpha}{\partial\delta_{minta}}\right)^2}{\alpha^2}}$$

where $\delta\alpha$ [W/(m^{2}K)] is the quadratic absolute error of the heat transfer coefficient, α [W/(m^{2}K)] is the heat transfer coefficient, $\delta\Delta T_{ref}$ [K] is the temperature measurement error of the reference cylinders, $\delta\Delta T_{ref,felület}$ [K] is the measurement error of the temperature of the reference cylinder surfaces, $\delta\delta_{minta}$ [m] is the error of the measurement of sample thickness. The maximum quadratic absolute error of the measurement was 4.77 % with the equipment I developed, at temperature differences of 5, 10, 25, 50 and 70 °C, and at pressures of 25, 50, 100, 250 and 500, measured on polypropylene specimens.

Thesis 6

I proved that as temperature difference and pressure are increased, the heat transfer coefficient between the polymer melt and the wall of the injection mold increases logarithmically with the temperature difference, according to the formula below:

$$\alpha(p,\Delta T) = C_{12}\cdot\ln\left(\frac{\Delta T + C_{13}}{C_{13}}\right)\cdot\frac{1-e^{-k\cdot p^l}}{1+e^{-k\cdot p^l}}$$

where p [bar] is the pressure between the polymer and the mold, k [1/bar], l [-], C_{12} [W/m^{2}K] and C_{13} [K] are constants and ΔT [K] is the temperature difference between the surfaces. The formula is valid in the temperature range 30 °C≤$T_{polymer}$≤200 °C and in the pressure range 0 bar≤p≤500 bar.

In the case of polypropylene and steel materials, at temperature differences of 5, 10, 25, 40, 50 and 70 °C, at pressures of 25, 50, 100, 250 and 500 bar, with the use of constants k=0,18 [1/bar], l=0,38 [-], C_{12}=345,3 [W/(m^{2}K)], and C_{13}=2,28 [K], the maximum relative error of the obtained heat transfer coefficient is 29 % [9].

6. My own publications

Journal articles

1. **Zink B.**, Szabó F, Hatos I, Hargitai H, Kovács J G: DMLS szerszámbetétek szimulációs vizsgálata, Műanyag- és Gumiipari Évkönyv, 12, 80-87 (2014)
2. Kovács J. G., Szabó F., Kovács N. K., Suplicz A., **Zink B**., Tábi T., Hargitai H.: Thermal simulations and measurements for rapid tool inserts in injection molding applications, Applied Thermal Engineering (IF=**2.624**), 85, 44-51 (2015)
3. Tabi T., Suplicz A., Szabo F., Kovacs N. K., **Zink B.**, Hargitai H., Kovacs J. G.: The analysis of injection molding defects caused by gate vestiges, Express Polymer Letters (IF=**2.953**), 9, 394-400 (2015)
4. **Zink B.**, Szabó F., Hatos I., Suplicz A., Kovács N. K., Hargitai H., Tábi T., Kovács J. G.: Enhanced Injection Molding Simulation of Advanced Injection Molds, Polymers (IF=**3.364** (2016)), 9, 1-11 (2017)
5. **Zink B.**, Kovács J. G.: The effect of limescale on heat transfer in injection molding, International Communications in Heat and Mass Transfer (IF=**3.718** (2016)), 86, 101-107 (2017)
6. **Zink B.** Kovács J. G.: Enhancing thermal simulations for prototype molds, Periodica Polytechnica Mechanical Engineering (accepted for publication)
7. **Zink B**., Kovács N. K., Kovács J. G.: Thermal analysis based method development for novel rapid tooling applications International Journal of Thermal Sciences (IF=**3.615** (2016)) (under review)

Conference articles

8. **Zink B.**, Kovács N. K., Kovács J. G.: Hűtőkörök hatása a fröccsöntési technológiára, XXIII. Nemzetközi Gépészeti Találkozó - OGÉT 2015, Csíksomlyó, 411-414 (2015)
9. **Zink B.**, Suplicz A., Szabó F.: Szimulációs modellfejlesztés, XXIV Nemzetközi Gépészeti Találkozó - OGÉT 2016, Déva, 503-506 (2016)
10. **Zink B.**, Suplicz A., Szabó F.: Fröccsöntött termékek vetemedésének csökkentése üveggyönggyel, XXVI Nemzetközi Gépészeti Találkozó - OGÉT 2018, Marosvásárhely, 537-540 (2018)

Conference presentations

11. **Zink B.**, Kovács N. K., Kovács J. G.: Hűtőkörök hatása a fröccsöntési technológiára, XXIII. Nemzetközi Gépészeti Találkozó - OGÉT 2015, Csíksomlyó, 2015.04.23-26., szóbeli előadás
12. **Zink B.**, Kovacs J.G.: Vízkőlerakódás hatása a fröccsöntő szerszámok hőtranszport folyamataira, X. Országos Anyagtudományi Konferencia, 2015.10.11-13., poszter
13. **Zink B.**, Suplicz A., Szabó F.: Szimulációs modellfejlesztés, XXIV Nemzetközi Gépészeti Találkozó - OGÉT 2016, Déva, 2016.04.21-24. szóbeli előadás
14. **Zink B.**, Suplicz A., Szabó F.: Fröccsöntött termékek vetemedésének csökkentése üveggyönggyel, XXVI Nemzetközi Gépészeti Találkozó - OGÉT 2018, Marosvásárhely, 2018.04.26-29., szóbeli előadás