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Prilagodljivi sistem za hlajenje orodij za brizganje plastike s pomočjo termoelektričnih modulov

An Adaptive System for Cooling Injection-Moulding Moulds Via Thermoelectric Modules

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Obvladovanje temperaturnih razmer v orodjih za brizganje plastike je eden izmed pomembnejših dejavnikov pri razvoju in izdelavi orodij. Trenutno nadzor nad temperaturami temelji na sistemu hladilnih kanalov v orodjih, po katerih hladilno sredstvo dovaja ali odvaja potrebno toploto prek celotnega orodja. Zmogljivosti opisanega sistema so zaradi narave tehnologije v veliko primerih nezadostne potrebam v industriji, ki narekujejo hitre in locirane spremembe temperatur v orodjih.

Obsežna študija termodinamičnih pojavov je pokazala, da toplotni tok v orodjih lahko poteka termoelektrično. Predstavljeni sistem nadgrajuje običajne hladilne sisteme, lahko pa deluje tudi kot neodvisen sistem. V prvem primeru sestoji iz enote za merjenje temperatur v orodjih, krmilne enote in termoelektričnih elementov kot izvršilnih elementov. Samostojen sistem potrebuje dodaten prenosnik toplote. Vse enote sestavljajo sklenjeno krmilno zanko.

V predstavljenem delu pisci predstavljajo rezultate raziskovalnega dela, ki sestoji iz treh delov, rezultati pa so patentno zaščiteni v A686\2006. Poglavitni rezultati tako testnega, prototipnega kakor tudi industrijskega sklopa se izražajo v hitri in popolnoma obvladljivem krmiljenju temperature preko celotnega delovnega kroga in vplivih le-te na kakovost plastičnih izdelkov s poudarkom na obvladovanju deformacij.

Predstavljena tehnologija in uporaba sta pomemben mejnik na področju obvladovanja temperaturnih razmer in kakovosti končnih izdelkov pri postopku brizganja plastike.

(Ključne besede: brizganje polimerov, pojavi termodinamični, hlajenje orodij, moduli termoelektrični)

One of the basic problems in the development and production process of moulds for injection moulding is the control of the temperature conditions in the mould. Nowadays, the temperature is controlled through a mould cooling system, which is composed of cooling channels, where the cooling fluid transports the needed heat to and from the mould. Such systems control the heat-exchange process throughout the entire mould, which is insufficient in many cases. For this reason it is necessary to develop a new system that will allow fast and precisely located temperature changes in defined mould locations.

A precise study of the thermodynamic processes in moulds showed that heat exchange can be manipulated by thermoelectrical means. Such a system upgrades conventional cooling systems within the mould or can be a stand-alone application for the heat manipulation within it. The upgraded system comprises the temperature-detection unit, the thermo-control unit and the final controlling element (thermo-element module as a heat pump), while the stand-alone unit needs an additional heat exchanger. These units form an adaptive closed loop.

In this paper we present the results of a research project that was carried out in three phases, and its results are included in the A686\2006 patent. The testing stage, the prototype stage and the industrialisation phase will be presented. The main results of the project were the total and rapid online thermo-control of the mould over the cycle time and the overall influence on the quality of the plastic product, with an emphasis on deformation control.

This system represents a milestone in the field of mould-temperature and product-quality control during the injection-moulding process.

(Keywords: injection moulding, thermal processes, injection mould cooling, thermoelectric modules)

0 UVOD

Potreba po razvoju hladilnih sistemov s termoelektričnimi moduli (TEM) izhaja iz vsakdanjih problemov pri konstruiranju, izdelavi in uporabi orodij. Hladilni sistemi, ki so trenutno v uporabi, temeljijo na sistemu hladilnih kanalov, po katerih hladilno sredstvo prenaša toploto iz želene lokacije ali nanjo. Navadno se kot hladilno sredstvo uporablja voda, v temperaturno zahtevnejših primerih (gretje) se uporablja olje, za hlajenja pa podhlajeni plini. Vse naštete tehnologije imajo tehnološke omejitve, ki jih s sodobnimi računalniškimi paketi (metode končnih elementov, v nadaljevanju MKE) lahko napovemo, ne moremo pa se jim popolnoma izogniti (poglavje 2).

Rezultati najnovešje analize so pokazali, da trenutne tehnologije hlajenja s svojimi pomanjkljivostmi ne zadoščajo več vsakodnevno zahtevnejšim okvirom tehnoloških oken predelave polimerov.

Glavna omejitev predelave polimerov je trenutna nezmožnost hladilnih sistemov glede skrajševanja delovnih krogov in posledično zmanjševanja stroškov. Trenutne tehnološke (stroji) in polimerne zmožnosti nadaljnjega naglega optimiranja postopka so izčrpane [3].

Predelave polimerov temeljijo na prehodu toplote med plastičnim materialom in orodno votlino. Zaradi vseh navedenih dejstev in omejitev trenutno uporabljene tehnologije je očitna potreba po razvoju novejših tehnologij in njihovo uvajanje v industrijsko prakso.

Prenos predstavljene tehnologije v vsakdanjo prakso je bil izveden na postopku brizganja plastike, čeprav je možnost uporabe širša; v veliki večini proizvodnih postopkov, ki temeljijo na prehodu toplote.

0 INTRODUCTION

The development of the technology of cooling moulds via thermoelectrical (TEM) means derives from industrial practise and problems, i.e., during the design, the tool making and the exploitation of tools. Current cooling technologies are based on a cooling-channels system through which the cooling fluid transports heat to or from the desired location. Water is commonly used as the transport medium; however, oil is used in cases of high temperature (heating function), and under-cooled gases are used in cases of high cooling demands. All of these principles have technological limitations, and these limitations can be located and predicted in advance with finite element analyses (FEA) simulation packages; however, they cannot be completely avoided (Section 2).

The results of a diverse state-of-the-art analysis revealed that all existing cooling systems do not provide controllable heat-transfer capabilities appropriate for the demanding technological windows of current polymer-processing technologies.

Polymer processing is nowadays limited (in terms of shortening the production cycle time and within that reducing costs) only by the heat-capacity manipulation capabilities. Other production optimization capabilities have already been driven to the mechanical and polymer processing limitations [3].

Polymer processing is based on the heat transfer between the plastic material and the mould cavity. Based on this and the other mentioned technological and economic facts it is justified to invest in and invent new technologies for heat manipulation in polymer processing and transfer them to everyday industrial practise.

The transfer of TEM cooling technology to the industrial phase has been applied through the injection-moulding process, although it can be applied during most processes where heat manipulation is required.

1 TERMODINAMIČNI POJAVI V POSTOPKIH BRIZGANJA PLASTIKE

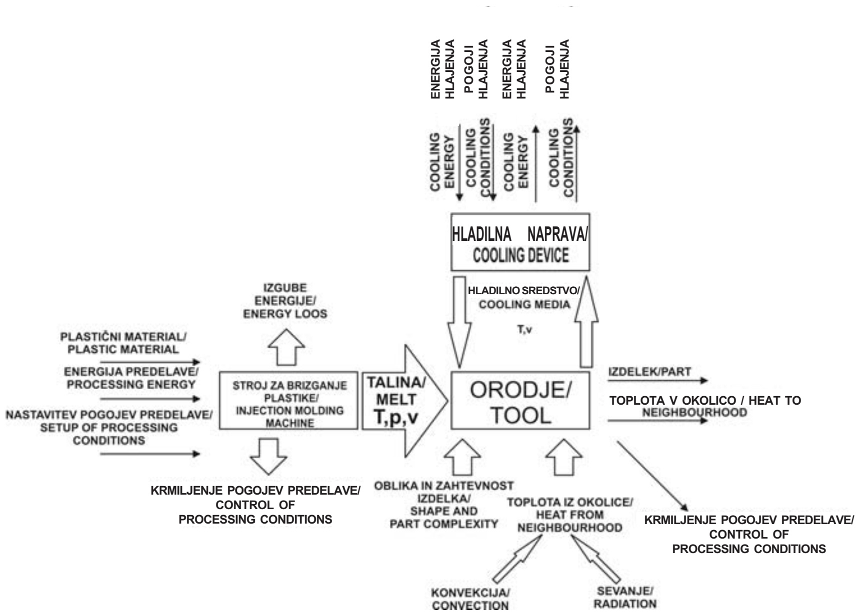
Pri postopku brizganja plastike se morata preučiti in upoštevati dve poglavitni dejstvi; celotna porabljena energija, ki temelji na prvem zakonu termodinamike (zakon o ohranitvi energije), ter hitrost prenosa toplote [1].

Osnovni nalogi termodinamične analize orodij za brizganje plastike sta časovni potek temperatur prek delovnega kroga ter fizična porazdelitev temperatur po orodni votlini. Slednja porazdelitev je

1 THERMAL PROCESSES IN INJECTION-MOULDING PLASTIC PROCESSING

As part of the calculation of heat transfer two major facts must be considered. First, all the used energy that is based on the first law of thermodynamics, i.e., the law of energy conservation [1], and the velocity of heat transfer.

The basic task during heat-transfer analyses is the calculation of temperature over time and its distribution inside the studied system. This last task depends on the velocity of the heat transfer between



Sl. 1. *Termodinamična shema postopka brizganja plastike [1]*
Fig. 1. *Thermodynamic block diagram for the injection-moulding process [1]*

odvisna od hitrosti prenosa toplote med opazovanim sistemom in okolico ter hitrostjo prenosa toplote v samem opazovanem sistemu [1]. Prenos toplote v orodjih temelji na prevodu, prestopu in sevanju [1], ki so nazorno predstavljeni na sliki 1.

1.1 Čas hlajenja

Delovni krog postopka brizganja plastike je sestavljen iz faze zapiranja orodja, brizga taline v orodno votlino, faze dodatnega tlaka za izravnavo skrčkov, faze hlajenja, faze odpiranja orodja in izmetavanja izdelka. V večini primerov je čas hlajenja najdaljši od vseh navedenih časov, kar pomeni tudi stroškovno največjo postavko v ceni izdelave in upravičuje nujnost raziskav na tem področju.

Čas hlajenja v postopku brizganja plastike je določen kot čas, potreben za ohladitev plastičnega kosa do temperature izmetavanja in je podan v enačbi:

the system and its surroundings, and the velocity of the heat transfer inside the system. Heat transfer is based on heat conduction, convection or radiation [1], and is described in the block diagram shown in Figure 1.

1.1 Cooling time

The complete injection-moulding process cycle comprises the mould-closing phase, the injection of the melt into the cavity, the packing-pressure phase for compensating the shrinkage effect, the cooling phase, the mould-opening phase and the part-ejection phase. In most cases the longest of all the phases described above is the cooling phase. Because it is closely related to costs, it is clear why it is reasonable to explore this field.

The cooling time in the injection-moulding process is defined as the time needed to cool the plastic part to the ejection temperature, and it is described by the following equation:

$$t_h = t_u + t_{np} + t_{ps} + t_{mr} + t_d \qquad (1),$$

kjer so:
t_h čas hlajenja, t_u čas brizga, t_{np} čas dodatnega tlaka, t_{ps} časa plastifikacije, t_{mr} časa morebitnega pomika plastifikatorja ter t_d kot dodatnega časa hlajenja [1].

with:
t_h as the cooling time, t_u as the injection time, t_{np} as the packing-pressure time, t_{ps} as the plastification time, t_{mv} as the movement of the injection time to the zero position and t_d as the additional cooling time [1].

Poglavitni cilj optimiranja postopka in razvoja predstavljene tehnologije je skrajšati čas t_d [1], ki je teoretično nepotreben, v praksi pa zaseda od 45% do 67% celotnega delovnega kroga.

Razmerje med pomembnimi temperaturami v postopku brizganja plastike so izkustveno podane z razmerjem:

The main aim of a cooling process is to lower t_d [1], which in theory is not necessary, but in practise it extends from 45% up to 67% of the whole cycle time.

The relationship between the important temperatures in the process of injection moulding is experimentally given by the following ratio:

$$\Delta T_U : \Delta T_K : \Delta T_T = 6:5:1 \tag{2}$$

kjer so:
ΔT_U sprememba temperature izmetavanja, ΔT_K sprememba temperature orodja in ΔT_T sprememba temperature taline.

Iz slednjega razmerja (2) je razvidno, kako pomembno vlogo ima temperatura orodja.

where:
ΔT_U is the deviation of the ejection temperature, ΔT_K is the deviation of the mould temperature and ΔT_T is the deviation of the melt temperature.

From this relationship one can conclude that the mould temperature has an enormous influence on the ejection time and therefore on the cooling time.

1.2 Temperaturne razmere v postopka brizganja plastike

Postopek brizganja plastike je krožni postopek, kakršen je tudi potek temperature površine orodne votline (sl. 2), ki se spreminja okoli srednje vrednosti.

Najvišja temperatura orodne votline je določena kot:

1.2 Temperature conditions in the injection-moulding processes

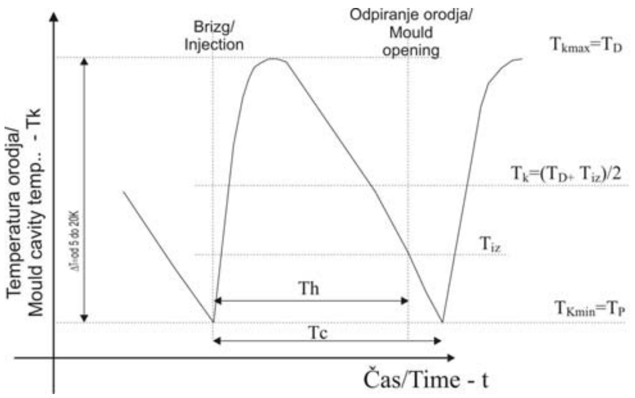
The injection-moulding process is a cyclic process where the mould temperature varies. As shown in Figure 2, the temperature varies around the average value through the whole cycle time.

The maximum mould temperature is defined as:

$$T_{KMAX} = T_D = \frac{T_P b_k + T_T b_P}{b_k + b_P} \tag{3}$$

kjer so:
$T_P = T_{KMIN}$ začetna temperatura orodne votline (nastavljiva vrednost), T_{KMAX} največja dosežena temperatura v orodni votlini, b_k toplotna prevodnost orodnih vložkov, b_P toplotna prevodnost polimera,

where:
$T_P = T_{KMIN}$ is the initial mould temperature of the cavity (adjustable temperature), T_{KMAX} is the maximum achieved temperature in the mould cavity, b_k is the mould-cavity heat conductivity, b_P is the polymer



Sl. 2. *Spreminjanje temperature orodja preko delovnega kroga [2]*
Fig. 2. *Mould-temperature during one cycle [2]*

T_P začetna temperatura orodnega vložka in T_T temperatura polimerne taline.

Enačba časa hlajenja plastičnega kosa se glasi:

$$t_h = \frac{b_0^{\ 2}}{K_0 \pi^2 a_{ef}} \ln\left(K_U \frac{T_T - T_K}{T_U - T_K} \right) \quad (4),$$

kjer so:
b_0 značilna izmera izdelka, a_{ef} toplotno prevodnostni koeficient snovi, K_U faktor oblike, T_T temperatura taline, T_K temperatura orodne vlo□ka ter T_U temperatura izmetavanja.

Termodinamični pojavi v orodjih za brizganje plastike (in drugih izdelovalnih postopkih) so dandanes dobro popisani s sodobnimi paketi MKE. Pred tem so bili v pomoč konstrukterjem orodij v pomoč t.i. nomogrami, diagrami z informacijami o porazdelitvi, prerezi itn. hladilnih kanalov glede na lastnosti plastičnega kosa. Trenutno se pri večini konstrukcij orodij uporabljata analiza in optimizacija termodinamičnih lastnosti orodja s sodobnimi paketi MKE zaradi tehnološke in ekonomske optimizacije proizvodnje. Zaradi navedenih analiz so omejitve hladilnih sistemov povezane in izvirajo samo iz omejitev hladilnega sredstva in konstrukcije hladilnega sistema (poglavje 2).

Opisane metode analiz v poglavju 2 so osnova nadaljnjemu razvoju sedanjih in v poglavju 4 opisani predstavljeni rešitvi hlajenja.

2 SEDANJI SISTEMI HLAJENJA V ORODJIH ZA BRIZGANJE PLASTIKE

Večina novih razvojev orodij gre preko postopka optimizacije hlajenja. Sodobni paketi termodinamičnih analiz temeljijo na metodah končnih elementov. Vstopni podatek slednjim analizam je več mogočih rešitev postavitve hladilnih kanalov, rezultati pa so natančne ocene termodinamične slike in potrebnega časa hlajenja.

2.1 Optimizacija hlajenja

Rezultati analiz poleg časa delovnega kroga (cena izdelave) obsegajo tudi posledice vpliva hlajenja na plastičnem kosu (kakovost izdelka).
a) Z optimizacijo temperiranja pridobimo vpliv na lastnosti kakovosti plastičnega kosa:
- videz površine in njena kakovost,
- zaostale mehanske napetosti,
- kristalizacijo,

heat conductivity, T_P is the mould-cavity starting temperature, and T_T is the polymer melt temperature.

The cooling time of the injection-moulded part time equation is:

where:
b_0 is the characteristic dimension, a_{ef} is the heat-conduction coefficient of the material, K_U is the shape coefficient, T_T is the melt temperature, T_K is the mould cavity temperature, and T_U is the ejection temperature.

The thermodynamic processes in the moulds for injection moulding (and other processing tools) can be well described using modern FEA tools. Common diagrams (nomograms) on design and thermodynamic relationships were used in the mould-design practise. Cooling-system design is nowadays carried out and analyzed by FEA tools in order to optimize the technological and economic aspects of production. That is why current cooling-system capabilities are limited only by the cooling media's properties and the construction limitation (Section 2).

The described methods for temperature control are the basis for extended use in further research activities. A special challenge is foreseen in the use of the described methods in new systems of cooling the moulds, which is presented in Section 4.

2 CURRENT COOLING TECHNOLOGY FOR PLASTIC INJECTION MOULDS

Most newly designed plastic parts go through an optimization of the cooling system before the realization of the mould. The modern concept of thermodynamic analyses is based on numerical FEA methods, and the results are a precise prediction of the production cycle based on the required cooling time.

2.1 Optimization of cooling

With the results of the cooling-system FEAs the cooling's consequences on the plastic part can be precisely explored in terms of product quality and cost.
a) With the optimization of the cooling, several plastic-part quality properties can be controlled:
- the surface appearance and quality,
- the residual stress rate,
- the crystallisation,

- toplotne deformacije,
- velikost in smer toplotnega zvijanja,
- razsežno stabilnost,
- sestavo materiala in usmeritev vlaken.

b) Prav tako pa so vsebina optimizacije tudi časi hlajenja in s tem povezana čas in cena izdelave:

- temperatura izmetavanja,
- delovni čas proizvodnje.

Oba navedena rezultata optimizacije (kakovost in cena izdelave plastičnega kosa) sta s trenutnimi orodji MKE natančno določljiva. Potek optimizacije temelji na iteraciji različnih možnosti postavitve hladilnih kanalov v orodju (spremembe računališkega modela orodja) in primerjanju medsebojnih rezultatov. Zaradi slednjih iteracij so opisane optimizacije inženirsko zapletene in časovno potratne (poleg časa delovnega kroga se optimirajo tudi lastnosti navedene v 2.1.a. Nenazadnje so zmogljivosti optimizacije hlajenja omejene z zmožnostmi hladilnega sredstva in same tehnologije hlajenja, opisane v 2.2 [3].

2.2 Konstrukcija hladilnih kanalov

Postavitev hladilnih kanalov v praksi poteka na podlagi izkušenj in razpoložljivega prostora v orodjih. Glede na omenjeno neenakomernost postavitve prihaja do oblikovanja t.i. “mrtvih con”, predstavljenih na slikah 3a in 3b. Mogoči izboljšavi tega problema sta povečanje števila hladilnih kanalov in zmanjšanje njihovega premera; slednje je navzdol omejeno z zamašitvijo kanalov zaradi odlaganja vodnega kamna (1 mm vodnega kamna ima enako toplotno upornost kakor 50 mm orodnega jekla [3]).

Na sliki 4 so vidne posledice neenakomerne postavitve hladilnih kanalov; natančneje, problemi učinka kota in dolgih tankih sten. Velike temperaturne spremembe po površinah orodja (sl. 4 levo) se kažejo v velikih zaostalih mehanskih napetostih, toplotnih deformacijah in razsežnostne nestabilnosti.

- the thermal deformation,
- the magnitude and direction of the thermal deflection,
- the dimensional stability of the product,
- the structure of the material and the fibers’ orientation.

b) Cost control as a consequence of manipulating the cooling time

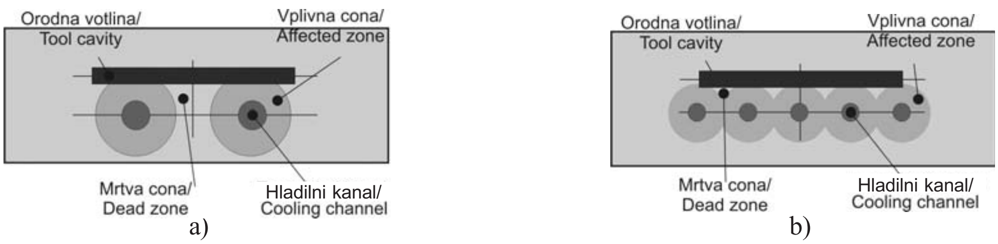
- the ejection temperature,
- the cycle time of the production.

Both stated issues (the quality and cost control) can be analyzed using state-of-the-art FEA tools. The optimization of the cooling is realized via an analyzed iteration, where the computer-aided design (CAD) of a design (cooling-system positioning) needs to be changed, and each such configuration later checked in the FEA environment for thermodynamic results. The described optimizations are, therefore, complex and time consuming (besides the cooling optimization, other properties stated in 2.1.a are also being optimized) but still cost efficient in terms of production cost saving. Finally, most optimization cases are limited by the current cooling system’s capabilities, and its properties are described in 2.2. [3].

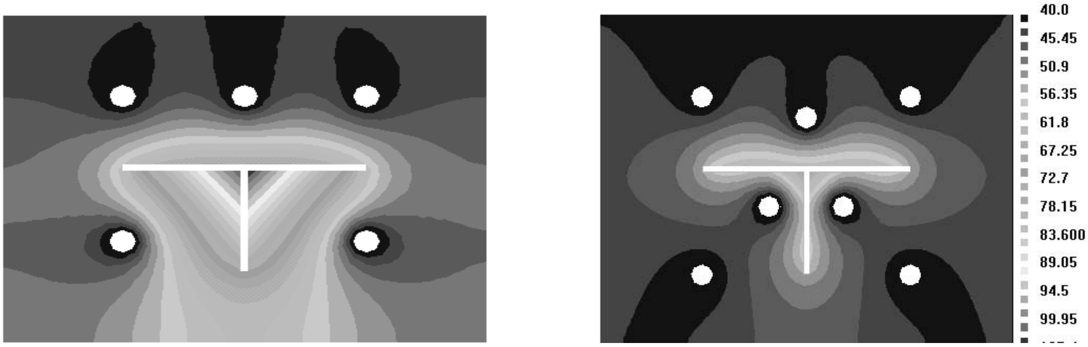
2.2 Design of the cooling channels

The positioning of the cooling channels is, in practise, based on experience and the available space inside the mould. Due to the fact that cooling is unevenly distributed the formation of “dead zones”, seen in Figures 3a and 3b is uneven. A possible solution to this problem is increasing the number of channels and decreasing the diameter of them where one must consider the problem of stuffing the channels with water limestone (1 mm of water limestone has a similar heat resistance to 50 mm of tool steel [3]).

The direct consequences of unevenly distributed cooling channels (corner effects, long thin ribs) can be seen in Figure 4. A high temperature variation results in a residual stress rate, thermal deformation and dimensional instability.



Sl. 3. *Vplivne cone glede na postavitev hladilnih kanalov*
Fig. 3. *Affected area due to positioning of the cooling channels*



Sl. 4. *Analiza učinka hlajenja kota z MKE*
Fig. 4. *FEA of a corner cooling effect*

Z uporabo termodinamičnih paketov MKE pri razvoju orodja se lahko temperaturno problematična mesta postavijo in kasneje z iteracijo variacij postavitve hladilnih kanalov (v okolju računalniško podprtega načrtovanja - RPN) se poišče temperaturno najboljšo rešitev. S tem se tehnološke omejitve trenutno uporabljenih tehnologij oz. posledice le-teh lahko omilijo ne moremo pa se jim izogniti.

Zaradi navedenih omejitev je treba razviti novo tehnologijo hlajenja, ki bo omogočala njihovo odpravo. Ena izmed takšnih je osnovana na termoelektričnih elementih.

3 HLAJENJE S TERMOELEKTRIČNIMI MODULI

Pobuda za razvoj nove hladilne tehnologije izhaja iz industrije in opisanih problemov, s katerimi se industrija vsakodnevno srečuje. Uporaba, opisana v nadaljevanju pa se lahko uporablja tudi v drugih pojavih in postopkih s potrebo po hitrih in nadzorovanih spremembah temperature.

3.1 Termoelektrični moduli (TEM)

Zveza med električnimi in toplotnimi lastnostmi temelji na Peltier-ovem učinku. TEM (sl. 5) je sestavljen iz mreže urejenih parov polprevodnikov tipa P in N. Slednji so vmeščeni med dve keramični osnovi, ki sta hkrati tudi prevodnika toplote TEM. Moč in smer črpanja toplote je enoznačno definirana s polarito in višino napajalne električne napetosti [4].

3.2 Uporaba za hlajenje orodij za brizganje plastike

Temelj uporabe je vgradnja TEM-ov v stene orodne votline, ki prevzemajo vloge ustvarjanja

With use of FEM packages during the design phase of the part and the mould for the injection moulding problematic spots can be located in advance. With an iterative approach in computer-aided engineering (CAE) the phase physical reparation of moulds can be avoided, although water-cooling technology limitations cannot be avoided.

To avoid all the mentioned problems and to enhance the cooling process in the mould some new approaches need to be considered. One of such approaches is cooling-process control by electrical means.

3 COOLING APPLICATIONS WITH THERMOELECTRIC MODULES

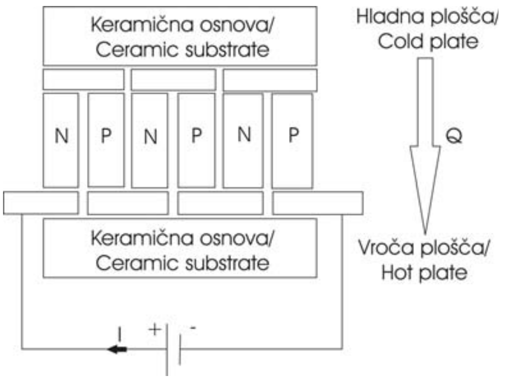
The initiative for exploring new technology has come from industry on the basis of the described facts and the current cooling-technology limitations. The solutions described in this paper can be used in applications where technology deals with heat transfer.

3.1 Thermoelectric modules (TEM)

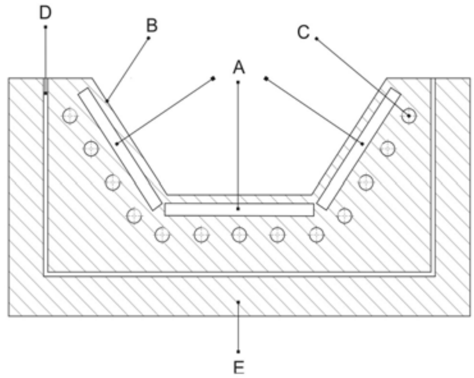
The relationship between the heat and the electrical variables is based on the Peltier effect. A TEM module (see Figure 5) is a device composed of properly arranged pairs of P- and N-type semiconductors that are positioned between two ceramic plates forming the hot and cold thermoelectric cooler sites. The power of heat transfer can be easily controlled through the magnitude and the polarity of the supplied voltage [4].

3.2 Application for mould cooling

The main idea of the application is inserting TEM modules into walls of the mould cavity to serve



Sl. 5. *Shema termoelektričnega modula*
Fig. 5. *Thermoelectric module block diagram*



Sl. 6. *Vgradnja TEM-a v orodje*
Fig. 6. *Structure of TEM cooling assembly*

primarnega toka toplote. Takšna osnovna zgradba sklopa je predstavljena na sliki 6. Sekundarni tok toplote je uresničen z običajnim hladilnim sistemom, ki odvaja/dovaja toploto iz okolice ali v okolico do termodinamičnega sistema orodja.

Sklop, predstavljen na sliki 6, sestoji iz termoelektričnih modulov (A), ki zagotavljajo primarni prenos toplote s temperaturno nadzorovane površine orodja ali nanjo (B). Sekundarni prenos toplote je uresničen z običajno tehnologijo hladilnih kanalov (C); omenjeno sekundarno toploto pa TEM-i prečrpavajo po nastavljivih časovnih in temperaturnih potekih. Za zmanjšanje toplotne vztrajnosti oblikovnega vložka orodja (F) skrbi toplotna izolacija (D), ki oblikovni vložek ločuje od toplotne vztrajnosti preostalih delov orodja (E).

Celotna uporaba je sestavljena iz TEM-ov (sl. 7), temperaturnih zaznaval in elektronske enote, ki skrbi za pravilno delovanje sistema. Poleg tega sistem vsebuje tudi vhodno enoto (uporabniški vmesnik), napajalno enoto ter močnostno elektronsko enoto (most H).

Vsi omenjeni elementi sestavljajo zaključeno krmilno zanko, prek katere elektronska enota poskuša slediti želenim temperaturno časovnim potekom.

Opisani sistem je zmožen delovanja v režimu hlajenja ali gretja, kar omogoča popoln nadzor temperatur v orodju prek celotnega delovnega kroga. Poleg tega omogoča sledenje različnim temperaturno časovnim potekom; tako za zagonske kakor ustavitvene režime delovanja.

Izvedba je s slednjo lastnostjo uporabna na vseh postopkovno proizvodnih področjih z

as a primary heat-transfer unit. Such a basic assembly can be seen in Figure 6. Secondary heat transfer is realized via a conventional fluid-cooling system that allows heat flows in and out of the mould cavity's thermodynamic system.

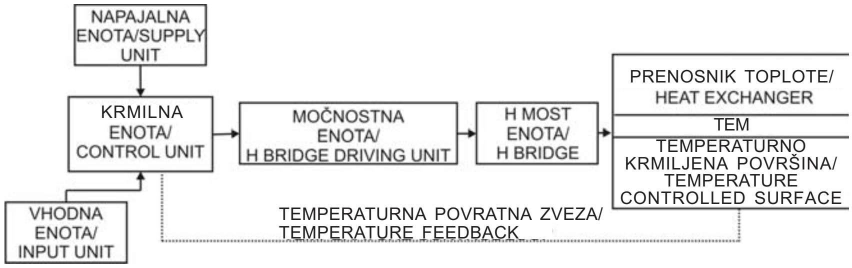
The device presented in Figure 6 is composed of thermoelectric modules (A) that enable primarily heat transfer from or to the temperature-controllable surface of a mould cavity (B). The secondary heat transfer is enabled via cooling channels (C) that deliver constant temperature conditions inside the mould. The thermo-electric modules (A) operate as a heat pump, and as such manipulate with the heat derived to or from the mould by the fluid-cooling system (C). The system for secondary heat manipulation with cooling channels works as a heat exchanger. To reduce the heat capacity of the controllable area thermal insulation (D) is installed between the mould cavity (F) and the mould structure plates (E).

The whole application consists of TEM modules, a temperature sensor and an electronic unit that controls the complete system. The system seen in Figure 7 also comprises an input unit (input interface) and a supply unit (unit for electronic and power electronic supply – H bridge unit).

The input and supply units with the temperature-sensor loop information are attached to a control unit that acts as an execution unit trying to impose predefined temperate/time relations.

Such a system can achieve heating as well as cooling operations. This enables the complete control of processes in terms of temperature and times through the whole cycle. Furthermore, it also allows various temperature/time profiles within the cycle for the starting and ending procedures.

The described technology can be used for various industrial, research and medical purposes where a



Sl. 7. *Shema sistema za hlajenje površin v okviru 0,1 K*
Fig. 7. *Structure for temperature detection and the control of surfaces to within 0.1 K*

zahtevami po natančnem temperaturno-časovnem nadzoru.

Predstavljana izvedba s slike 7 je bila raziskana in preizkušena na dveh ravneh, in sicer v okolju MKE ter dejanskem, prototipnem okolju. Obe okolji sta namenjeni za medsebojni in obojesmerni nadzor rezultatov in boljše razumevanje problemov termodinamike.

4 ANALIZA Z MKE

Sodoben razvoj orodij za brizganje plastike je sestavljen iz več faz. Ena izmed njih je tudi konstrukcija in optimizacija hladilnega sistema. Slednje opravilo pa se izvaja v okviru namenskih paketov MKE (Moldflow, Moldex…[3]), ki uspešno napovedo zmogljivosti hladilnega sistema in njihov vpliv na mehanske lastnosti plastičnih kosov. Z iteracijo optimizacije v okolju MKE se optimira delovni krog in parametri brizganja s popolnim nadzorom nad kakovostjo in reologijo plastičnih izdelkov.

Reološki rezultati simulacij so navadno točni in zanesljivi v primerih natančnih popisov snovnih parametrov. Glede na visoko stopnjo prirejenosti tovrstnih paketov MKE je analiza tehnologij, ki so drugačne kakor sedanji hladilni sistemi, zelo otežena. Zaradi navedenega, se je za potrebe analiz predstavljene izvedbe, uporabilo splošnejše pakete MKE.

4.1 Fizikalni model, analiza z MKE

Uvajanje analiz MKE v razvoj predstavljene tehnologije je bilo izvedeno zaradi izkušenj na področju [3] in možnosti nadzora različnih parametrov znotraj računalniškega okolja. Celoten resnični prototip je bil preslikan v okolje MKE (sl. 8), kjer je

precise temperature/time control is required; in fact in some applications it is already being implemented.

The presented system in Figure 7 needs to be evaluated from the theoretical as well as from the practical point of view. The theoretical aspect was evaluated by the FEM simulations, while the practical one was evaluated by the development of the prototype and real application testing. FEM simulations also served as support control during prototype testing and vice-versa.

4 FEM ANALYSIS

The current development of designing moulds for injection moulding consists of several phases. Among them is the design and optimization of a cooling system. This involves days of simulations using customized FEM packages (Moldflow, Moldex, etc. [3]) that can predict cooling-system capabilities and especially its influence on plastic. With such an iteration in the FEM environment the mould designers gather information on rheological data, deformation and esthetical information due to shrinkage and production time-cycle information.

This thermal information is usually accurate but can still be unreliable in cases of insufficient information about the rheological material. Although such FEM packages are frequently used, mould designers cannot depend entirely on the results of simulations. Furthermore, due to the customization of such packages, they are of limited use in our development where more common FEM packages had to be used.

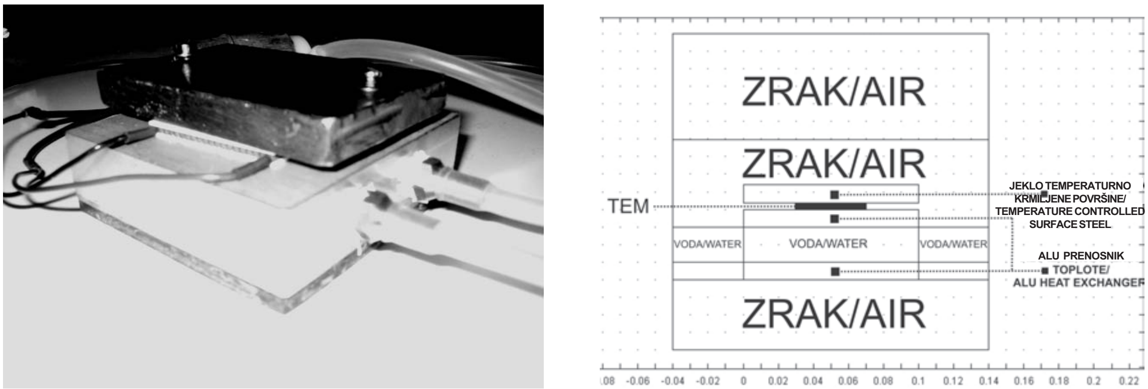
4.1 Physical model, FEM analysis

The implementation of FEM analyses into the development project was done as a result of long experiences with such packages [3] and the possibility to perform different tests in a computer environment. The whole prototype cooling system was bila izvedena termodinamična analiza posameznih sklopov prototipa in prestopnih pogojev med njimi. Glede na ozko prirejenost sedanjih paketov MKE in nezmožnost analiziranja različnih prestopnih pogojev med elementi prototipa in popisa TEM, delujočega v režimu toplotne črpalke, je bilo izbrano splošno fizikalno okolje MKE COMSOL Multiphysics. Slednje omogoča hkratno analizo več fizikalnih veličin (toplotni tok, pretok tekočin, elektromagnetne veličine itn.). Termodinamični rezultati prenosa dejanskih lastnosti prototipa v okolje MKE so bili primerjani z dejanskimi rezultati prototipnih preizkusov. S tem je bilo omogočeno optimiranje parametrov simuliranja samega elementa TEM z namenom natančnega popisa celotnega sklopa in pridobitve zanesljivih rezultatov termodinamičnih analiz. Analiza z MKE je potekala z upoštevanjem dveh poglavitnih fizikalnih veličin. Analizirana sta bila dva toplotna vira, in sicer, prevajanje in prestopanje (sevanje je bilo zaradi razmeroma nizke temperature in majhnega vpliva na temperaturo zanemarjeno) za analizo TEM ter prevajanje in prestopanje z vplivom dinamike tekočin za analizo vodnega prenosnika.

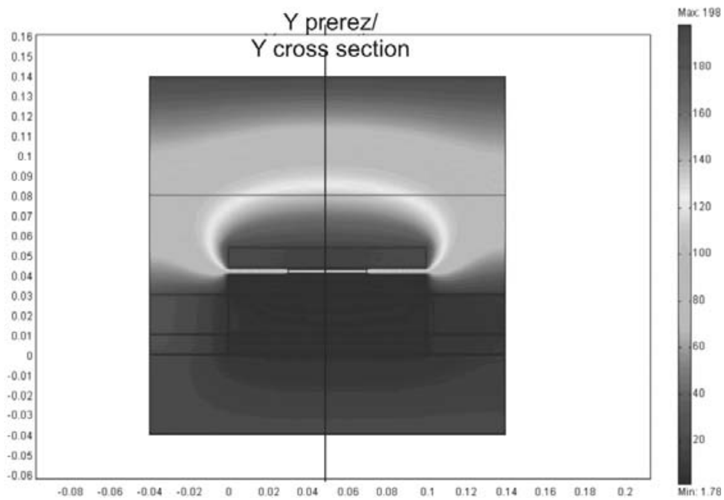
Slika 8 predstavlja oba prototipa, v resničnem in prerez prototipa v simulacijskem okolju. Na levi sliki je prikazan resničen prototip, pri katerem je spodnji segment aluminijast vodni prenosnik, sredinski člen je TEM, zgornji jekleni blok pa nadzorovano površino. Enaka sestava je bila simulirana v okolju MKE s poudarkom na pravilno opisanem modelu člena TEM, kar je bilo doseženo s sinhrono primerjavo preizkusov v dejanskih razmerah. Skratka, model na osnovi MKE je bil popisan in optimiziran z uporabo enakih preizkusov

designed in a FEM environment (see Figure 8) through which the temperature distribution in each part of the prototype cooling assembly and the contacts between them were explored. Customized packages for heat-transfer simulation inside moulds were not appropriate due to the limited input designs; in those packages it is not possible to implement a device like a TEM working as a heat pump, and also the contacts seen in Figure 6 cannot be properly described. For simulating physical properties inside a developed prototype a simulation model was constructed using the COMSOL Multiphysics software. This package enables multiphysics modelling, taking into account several physical phenomena (heat transfer, fluid flow, electromagnetic fields, etc). The result was a FEM model identical to the real prototype through which we were able to compare and evaluate the results. The FEM model was explored in terms of heat-transfer physics, taking into account two heat sources: a water exchanger with fluid physics and a thermoelectric module with heat-transfer physics (only conduction and convection were analyzed, radiation was ignored due to the low relative temperature and therefore the low impact on temperature).

Figure 8 shows both prototypes: the real one and a cross-section of the prototype in the FEM environment. In the left-hand figure the lower sections represent the water heat exchanger in aluminium; the middle layer represents the TEM in cooling operation; while the upper layer represents a steel block that requires its temperature to be controlled. The structure in Figure 8 has been explored in detail: the FEM model of the TEM was designed and synchronized with tests of a real TEM, and with those data the heat parameters were gained and the model was tuned up in order to achieve the correct properties.



Sl. 8. *Prototip v resničnem (levo) in okolju MKE (desno)*
Fig. 8. *Prototype in real (left) and FEM environment (right)*



Sl. 9. *Porazdelitev temperature znotraj obravnavanega sistema prototipa glede na analizo z MKE*
Fig. 9. *Temperature distribution according to FEM analysis through the prototype*

v dejanskih razmerah. Rezultat pa je bil zanesljiv simulacijski model, ki se uporablja za optimiranje resničnih uvajanj predstavljene izvedbe v orodjih.

Začetni (okolica modela) in robni pogoji (stalno prisilno stanje vodnega prenosnika) analiz z MKE so bili nastavljeni na 20 °C.

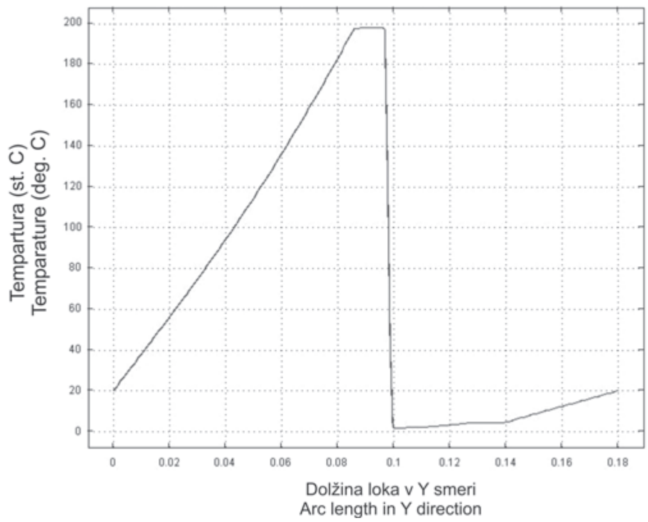
Slika 9 prikazuje temperaturno polje okrog modela po MKE v ustaljenem stanju (končan prehodni pojav) slike 8. Rezultati te simulacije prikazujejo ujem resničnega prototipnega in okolja MKE.

Prav tako pa so bili izvedeni prehodni pojavi, tako v prototipnem (sl. 11) kakor okolju MKE.

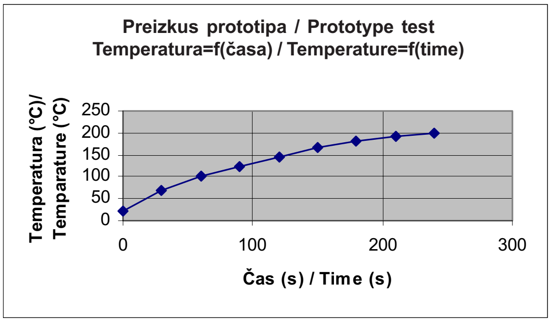
The boundary conditions for the FEM analyses were set so as to achieve identical working conditions as in the real testing. The surrounding air and the water exchanger were set and forced at a stable temperature of 20°C.

The results of the FEM analysis can be seen in Figure 9, i.e., the temperature distribution field through the simulation area shown in Figure 8. Figure 9 represents a steady-state analysis, which was very accurate in comparison to the prototype tests.

Transient FEM analyses were also implemented. The transient results of a real prototype are shown in Figure 11.



Sl. 10. *Potek temperature po prerezu Y glede na sliko 9*
Fig. 10. *Temperature distribution across the Y cross-section according to Fig. 9*



Sl. 11. *Prehodni temperaturni odziv resničnega prototipa s slike 7*
Fig. 11. *Transient temperature response of a real prototype test from Figure 7*

Nazornejši prikaz poteka temperature vzdolžnega prereza Y s slike 9 je ponazorjen s sliko 10.

Vroča stran TEM (najtoplejša točka sklopa) se je segrela na približno 200 °C, medtem ko je bila temperatura hladne strani 5 °C. Tako velike temperaturne razlike na samem TEM se kažejo v velikih mehanskih napetostih, kar privede do mehanskega uničenja TEM. Zaradi tega je treba veliko pozornosti posvetiti mehanskim spojem in pritrditvam TEM kakor tudi inteligentni elektronski zaščiti krmilne enote (glej poglavje 3.2).

Kakor je bilo že omenjeno, so bili opravljeni tudi prototipni preizkusi. Na sliki 11 je prikazan prehodni pojav celotnega sklopa. Ob času 0 je na TEM skočno obremenjen s polno vrednostjo električne moči v delovnem režimu gretja (začetni in robni pogoji so bili postavljeni enako kakor na preizkusu s slike 8).

Bilo je več razlogov za simulacijo z MKE. Prvi leži v preizkusu toplotnih lastnosti posameznih snovi v sklopu in stikov med njimi, medtem ko je drugi temeljen z boljšim razumevanjem pridrode pojava.

Trenutno delo poteka tudi v smeri nadaljnjega optimiranja modela po MKE na podlagi različnih prototipnih preizkusov v dejanskem okolju. Z rezultati vseh preizkusov in optimiranim modelom TEM in spojev bodo rezultati simulacij celotnih sklopov in uporabe pri dejanskih orodjih prepričljivejši.

4.2 Elektronska krmilna enota

Za potrebe krmiljenja hladilnega postopka celotne naprave je bilo treba razviti namensko krmilno enoto, ki bo zmo na vzporednega nadzora

The temperature distribution over the vertical cross section shown in Figure 9 can be seen in Figure 10.

Figure 10 represents the highest temperature, just below 200°C at the TEM surface on the hot side, while the cold side cools to approximately 5°C; both ends of the curve converge to the surrounding temperature of 20°C. Such a high temperature difference in the TEM results in a high mechanical stress, which can lead to a TEM physical break. Those problems are solved by several solutions, such as correct mounting, choosing an appropriate TEM and applying intelligent electronic control (see Section 3.2).

Transient analyses and a prototype test were also performed, as already described. Figure 11 shows the transient response of the temperature at the controllable surface when driving the TEM with a unit pulse (at time 0 s full heating was applied and the starting conditions were set to 20°C).

There were several reasons for using a FEM model simulation. The first reason was to test the thermal properties of different materials and the bonds between them, while the second was to gain a better understanding of the underlying physics.

After getting a satisfactory FEM model with a behaviour that was similar to the real prototype, some fluid tests were made to test different fluids and their heat-transfer abilities. Fine tuning of the FEM model was carried out according to real testing, which is why the FEM analyses showed precise results.

4.2 Electronic control unit

In order to control the cooling process with TEM, the control unit also needs to be developed and adapted to the process needs. The control unit must be able to več različnih TEM po različnih temperaturno-časovnih potekih znotraj orodja za brizganje plastike. Omenjena krmilna nadzorna enota deluje na načelu mehke logike zaradi narave termodinamičnega modela, kratkih odzivnih časov in enostavnosti samega krmiljenja. V primerjavi s PID krmiljenjem se mehko krmiljenje izkaže z večjo odzivnostjo ob enakih zahtevah natančnosti ([7] in [8]). Omenjeno mehko krmiljenje je zagotavljalo veliko natančnost 0,1 K ob izredno hitrih odzivih.

Gonilna enota za močnostno enoto (most H, slika 7) je uporabljala impulzno širinsko modulacijo (IŠM - PWM) z nosilno frekvenco 1kHz. Slednja frekvenca je bila izbrana na osnovi kompromisa med največjo učinkovitostjo TEM (valovitost električnega toka naj ne bi bila večja od 5%), zmanjšanjem izhodnega filtra za glajenje omenjenega toka in zmanjšanjem preklopnih izgub na mostu H.

5 PREGLED RAZVOJNIH FAZ PROJEKTA

Celoten projekt razvoja izvedbe je bil zaradi zapletenosti razdeljen na več faz:

a) Prototipna faza; osnovni preizkusi uvajanja TEM v krožni režim delovanja kot črpalke toplote, izdelava prototipa sklopa;
b) Preizkusi v okolju MKE; izdelava modela TEM in optimiranje le-tega glede na rezultate dejanskega prototipa; preizkusi celotnega sklopa v okolju MKE ter preizkušanje različnih snovi, konstrukcij itn.;
c) Izdelava preizkusnega orodja za brizganje plastike; izdelano je bilo orodje za preizkušanje skrčkov različnih snovi z veliko zahtevnostjo obvladovanja temperatur; hlajenje s TEM je potrdilo velika pričakovanja (sl. 12);

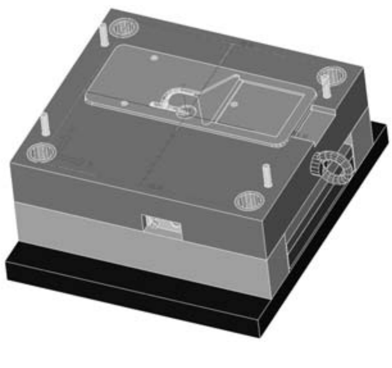
control the temperature on all the needed areas in the mould during the whole injection-moulding cycle. Therefore, the already described electronic unit is based on fuzzy logic due to the nature of the regulation system, short response times and simplicity. Classical PID control was not chosen because the required accuracy with fuzzy logic was gained using shorter control cycle times ([7] and [8]). There are more parameters to be calculated during PID control and, therefore, the required control cycle time is longer and yet there was no need for higher accuracy (below 0.1 K).

The driving unit for the H Bridge seen in Figure 7 was applied with pulse width modulation (PWM) and the modulating frequencies set to 1 kHz. Such frequencies were chosen to ensure the maximum efficiency of the TEM (the ripple in the electric current should not exceed 5%), physically minimize the output filter unit and minimize the switching losses on the H bridge.

5 DEVELOPMENT PHASE REVIEW

The whole development project was, due to its complexity, divided into several phases:

a) Prototyping phase: tests for the implementation of the TEM into cyclic operation in injection moulds were made.
b) Tests of the FEM environment were implemented: data from the FEM analysis were fine tuned according to the tests on the prototype. Results were the control parameters, on the one hand, and materials, construction and data on fluid properties, on the other.
c) With all these gathered data the project went into the final testing phase: a mould for injection moulding for the measurement of default shrinkage for the plastic material was constructed, realized and can be seen in Figure 12.



Sl. 12. *RPN model orodja (levo) in preizkus predstavljene izvedbe (desno)*
Fig. 12. *CAD model of a mould (left) and a test of the presented application (right)*

d) Z vsemi preizkusnimi prototipnimi in industrijskimi podatki je bila narejena primerjalna analiza običajne in predstavljene tehnologije hlajenja orodij za brizganje plastike; ugotovljene so bile izboljšave in omejitve predstavljene izvedbe.

6 SKLEPI

Vnos tehnologije termoelektričnih modulov z neposredno zvezo med električnimi in toplotnimi lastnostmi pomeni pomemben mejnik v razvoju problematike hlajenja orodij. Prenos slednje v zapleteno problematiko hlajenja orodij za brizganje plastike pa prinaša velika pričakovanja pri izdelavi plastičnih izdelkov velikih tehničnih zahtev.

Predstavljena izvedba omogoča popolno obvladovanje zapletenih toplotnih razmer v orodjih za brizganje plastike v smislu nastajanja različnih temperaturnih potekov prek delovnega kroga. Prav tako odpravlja pomanjkljivosti neenakomernega hlajenja z običajno tehnologijo pri izdelavi zelo estetskih izdelkov (površine A). Z možnostjo trenutnega predgretja problematičnih lokacij ob času polnjenja odpravlja problematiko zapolnitve tankih reber. Ena najpomembnejših lastnosti izvedbe (z omenjenim časovno temperaturnim potekom, ki so lahko različni za različne lokacije v orodju oz. TEM) je nadzor in možnost vpliva na velikost in smer toplotnega zvijanja plastičnega izdelka. Poleg vseh naštetih izboljšav pa predstavlja tudi vzpostavitev nadzora nad reološkimi lastnostmi plastičnih izdelkov, predstavljenih v poglavju 2.1.

Trenutno in nadaljnje delo je usmerjeno na tri področja. Prvo je industrializacija in nadaljnja optimizacija izvedbe, predvsem v smeri optimiranja krmilne enote z definiranimi strategijami, omejitvami in lastnostmi posameznih modelov hladilnih sistemov z namenom popolnega termodinamičnega nadzora nad toplotnimi pojavi v orodjih.

Drugi poudarek je na izvedbi popolnoma delujočega in resničnega računalniškega modela celotne izvedbe. Razvoj poteka v dveh smereh, in sicer v smeri razvoja računalniškega modela in simulacij termodinamičnih pojavov znotraj orodja (poglavje 4) ter v smeri razvoja računalniškega modela električnega krmiljenja sistema s slike 7. Oba prek električnih veličin povezana simulacijska modela bosta omogočala popoln vpogled v dejansko stanje, tako glede

d) This application needed precise and stable temperature conditions, and the tested application also proved to be appropriate in an industrial environment. With these tests a proper industrial comparison between the current cooling technology and the solution with TEM were performed, revealing the advantages as well as the limitations of the system.

6 CONCLUSIONS

The use of a thermoelectric module, with its straightforward connection between the input and output relations, represents a milestone in the solution to the cooling problem. Its introduction into moulds for injection moulding, with its problematic cooling construction, and the problematic processing of precise and high-quality plastic parts, represents a difficult challenge.

With the mentioned functionality of a profile temperature driving across the cycle time the injection-moulding process can be fully controlled. Industrial problems (presented in Section 2.1) such as the uniform cooling of problematic A-class surfaces and its consequence on the appearance of the plastic part can be solved. The problems of filling long thin walls can be solved with overheating some surfaces during the injection time. One of the most important application properties is the ability to control and influence the magnitude and direction of the thermal deflection of the plastic part. Furthermore, with such an application control over the rheological properties of plastic materials can be gained.

Current and future work is divided into three areas. The fisrt is industrialization and final tuning of the real application with an emphasis on the control unit where different strategies, limitations and model properties are being optimized in order to get the desired result, i.e., full control over the physical model's thermodynamic behaviour.

The second is focusing on creating a fully independent process in the computer environment. A FEM model of the thermodynamic behaviour of the physical model, i.e., assembly of the mould and TEM together, which we have already accomplished (Section 4) and the process model of the control unit that would represent a complete control unit, shown in Figure 7. Both computer environments will be linked together through real electric parameters – time-dependent electric current and voltage. With such a fully described and customized FEM model termodinamičnih kakor električnih veličin. Tako popisan model bo omogočal računalniško optimiranje termodinamičnih pojavov s predstavljeno izvedbo.

Tretji del razvoja pa zajema razširitev predstavljene izvedbe v ostale preoblikovalne ali nepreoblikovalne industrijske postopke s potrebo po zahtevnih temperaturnih parametrih.

we will be able to promptly adapt and optimize the parameters for diverse cooling systems in industrial practise while performing an optimization in the computer environment.

The third goal of our future work will be directed in the dissemination of the presented application in the processing or non-processing industry environment where heat manipulation is required.

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