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Izboljšanje procesa načrtovanja hladilnih sistemov pri kokilah za tlačno litje - občuten prispevek h kakovosti in življenjski dobi

Enhancing the Design Process of Cooling Systems for Die-Casting Dies - A Significant Contribution to Quality and Lifetime

Izvleček

Pri visokotlačnem kokilnem litju nastopajo velike ciklične temperaturne in mehanske obremenitve. Cikli segrevanja in ohlajanja povzročajo toplotne raztezke in skrčke materiala, ustvarjajo napetostna polja, kar vodi do občutne plastične deformacije. Kopičenje plastičnih deformacij pogosto pripelje do nepričakovanih poškodb površine kokil za tlačno litje. Izbira, kakovost in obdelava (npr. toplotna obdelava) orodnih jekel za vroče preoblikovanje so parametri, o katerih se razpravlja v znanstveni literaturi. Vendar je krmiljenje temperature kokil za tlačno litje dodaten pomemben parameter, da se doseže primerna življenjska doba. Prispevek osvetljuje, kako se lahko značilne lastnosti klasičnih notranjih hladilnih sistemov (npr. koeficient prestopa toplote na steno in zmanjšanje tlaka) izračunajo s CFD-simulacijo (CFD – computational fluid dynamics – računalniška dinamika fluidov, op. prevajalca) (ANSYS CFX) in preverijo eksperimentalno. Izračunane specifične vrednosti zmanjšanja tlaka in koeficienta za prenos toplote na steno so bile obdelane in uporabljene za tehnične specifikacije. S tem znanjem je proces načrtovanja hladilnega sistema natančnejši kot pri ocenjevanju, ki sloni na dobljenih praktičnih izkušnjah. Vendar smo zaradi omejitev pri delovanju klasičnih hladilnih sistemov razpravljali o alternativni metodi, kako določiti usklajene hladilne kanale: razdelitev tlačne kokile na segmente. Da bi prikazali možnosti, prednosti in omejitve te metode, smo uporabili vložek iz obstoječe tlačne kokile. Prispevek se konča s kratkim povzetkom in pregledom pristopov za nadaljnje izboljšave.

Ključne besede: tlačno litje, proces načrtovanja, krmiljenje temperature, CFD-analiza, usklajeni hladilni kanali

Abstract

High-pressure die-casting dies are subjected to high cyclic temperatures and mechanical loads. Heating and cooling cycles cause thermal expansion and contraction of the material, generating strain fields which lead to a significant plastic deformation. An accumulation of plastic deformations often leads to unexpected failures at the surface of the die-casting die. The selection, quality and the pro-cessing (e. g. heat treatment) of hot work tool steels are parameters that are often discussed in scien-tific literature. However, the temperature control of the die-casting die is another important parameter for the achievement of reasonable lifetimes. The article illustrates, how characteristic properties of conventional internal cooling systems (e. g. the wall heat transfer coefficient and the pressure drop) can be calculated by CFD simulation (Ansys Cfx) and verified by experimental investigations. The calculated specific values for the pressure drop and the wall heat transfer coefficient were processed and transformed into engineering specifications. Using this knowledge, the design process of the cool-ing system is more accurate than an estimated guess based on gained practical experience. However, due to restrictions in the performance of conventional cooling systems, an alternative method to estab-lish conformal cooling channels is discussed: the segmentation of the die-casting tool. In order to demonstrate the potential, advantages and restrictions of this method, an existing die-casting tool insert is used. The article finishes with a brief summary and an outlook on further improvements to the approaches.

Keywords: die-casting, design process, temperature control, CFD analysis, conformal cooling channels

1 Uvod

Notranji hladilni sistem v kokili za tlačno ulivanje aluminija je namenjen predvsem za ustvarjanje toplotne bilance na določeni temperaturni ravni. [MEN99] je ugotovil, da je stroškovna učinkovitost proizvodnega procesa v veliki meri odvisna od dejstva, ali je orodje za litje učinkovit toplotni menjalnik. Ta trditev se je prvotno nanašala na vbrizgovalno ulivanje polimerov. Vendar so naraščajoči stroški dela, stroški energije in zahteve po kakovosti upravičili, da se ta trditev lahko uporabi tudi za tlačno litje. V osnovi ima hladilni sistem v kokili za tlačno litje vpliv na naslednje tri glavne vidike tlačnega litja:

- **čas cikla pri tlačnem litju**: učinkovit hladilni sistem omogoča, da se iz kokile za tlačno litje odstrani velika količina toplote. Rezultat tega je skrajšan čas strjevanja, kar predstavlja dodatno skrajšanje časa cikla;
- **kakovost tlačno ulitih delov**: krmiljenje temperature in s tem krmiljeno strjevanje tlačno ulitega dela zmanjšuje na minimum tveganja za krčilne napake, ki se pojavijo, kadar ni na razpolago materiala za napajanje, da kompenzira krčenje, ko se kovina strjuje. Učinkovit hladilni sistem ima vlogo, da pospeši ohlajanje nestrjenih

1 Introduction

The internal cooling system of an aluminum die-casting die primarily serves to establish a heat bal-ance at a defined temperature level. [MEN99] stated that the cost effectiveness of the production pro-cess strongly relates to the question of whether the casting tool is an efficient heat exchanger. This statement was related to the injection moulding process originally. However, increasing labour costs, energy costs and demanding requirements in terms of quality justify the fact that this statement can also be seen in the context of the die-casting process. Basically, the cooling system of a die-casting die has an impact on the following three major aspects of the die-casting process.

- **The cycle time of the die-casting process**: An efficient cooling system enables the die-casting die to remove a high amount of heat. This results in a shortened solidification time which in turn implies a reduction of the cycle time.
- **The quality of the die-casting parts**: A temperature control and thus a controlled solidifica-tion of the die-casting part enable the minimization of the risk of shrinkage defects that occur when feed metal is not available to compensate

območij. Alternativno se lahko uporabi tudi za segretje lokalnih območij, da bi se zagotovil material za napajanje pri upočasnitvi strjevanja;

- **življenjska doba tlačno ulitega materiala**: predhodne raziskave so navadno osredotočene na kakovost orodnega jekla za vroče preoblikovanje. V tem oziru sta metalurška sestava in obdelava (tj. tehnologije obdelave staljene kovine, toplotna obdelava, razvoj površinskih prevlek) orodja za vroče preoblikovanje glavna kriterija. Cilj je ustvariti visokokakovostne materiale, da bi se povečala življenjska doba tlačno ulitega materiala. Zato je velika ciklična obremenitev zaradi toplotnih šokov neizogibno dejstvo. Glavna prednost učinkovitega hladilnega sistema je doseči zmanjšanje temperaturne razlike (in s tem zmanjšanje nateznih napetosti, ki jih povzroča toplota) med kokilo za tlačno litje in mazivom kokile na vodni osnovi na minimum.

Vsota vseh teh vidikov kaže, da se hladilni sistem lahko obravnava kot bistveni parameter pri zagotavljanju gospodarnosti tlačnega litja. Kljub temu obstaja več težav, ki jih je treba razčistiti. Dimenzioniranje hladilnega sistema često sloni na pridobljenih izkušnjah konstruktorja kokile in tu manjka sistematični postopek načrtovanja [LIN03],[LI05]. Navadno imajo kokile za tlačno litje omejeno odvajanje toplote in omejene toplotne izgube zaradi neusklajenih hladilnih kanalov z omejenimi površinami ter slabo možnostjo krmiljenja temperature kokile. Dodatno so se v zadnjem času razvile in vpeljale tehnologije, pri katerih se uporablja minimalna količina pršil [MUE 12]. Čeprav ima ta metoda pršenja zanemarljiv vpliv na toplotno bilanco kokile, obstajajo nadaljnji izzivi za razvoj notranjih hladilnih sistemov.

for shrinkage as the metal solidifies. An effi-cient cooling system possesses the function of an increased cooling of non-solidified areas. As an alternative, it serves to heat local areas in order to assure the feeding of material by decelerating the solidification process.

- **The lifetime of the die-casting material**: Preliminary research work commonly focused on the quality of the hot work tool steel. In this context, the metallurgical composition and the processing (e. g. molten metal processing technologies, heat treatment, development of surface coatings) of the hot work tool was regarded as a major criterion. The aim was to establish high-quality materials in order to strengthen the lifetime of the die-casting material. Conse-quently, the high cyclic loading due to thermal shocks was seen as an inevitable factor. The main advantage of an efficient cooling system is found in the minimization of the temperature difference (and thus in a reduction of thermally induced tensile strains) between the die-casting die and a water-based die lubricant.

The sum of all aspects indicates that the cooling system can be regarded as an essential parameter for ensuring an economic die-casting process. Nevertheless, there are several problematic issues that can be identified. The dimensioning of the cooling system is often based on the gained experience of the die-designer and lacks a systematic design process [LIN03], [LI05]. Usually die-casting dies exhibit a limited heat output and heat losses due to non-conformal cooling channels with limited surfaces and a poor controllability of the die temperature. In addition, the application of minimum quantity spraying technologies were developed and qualified recently [MUE12]. Since this spraying method has

Da bi spoznali preje omenjene izzive, je bil na Inštitutu za spajanje in varjenje pripravljen raziskovalni projekt. Strategija rešitve raziskovalnega projekta se je razdelila na dva pristopa: optimiranje z bolj učinkovitim dimenzioniranjem hladilnih kanalov in razdelitev kokile na segmente, da bi prišli do usklajenih hladilnih kanalov.

2 Osnove

2.1 Prenos toplote

Podrobne podatke o prenosu toplote med fluidom in trdnino lahko najdemo v številnih virih [BAE 12], [VDI06]. Da bi se osredotočili na glavno težavo, bomo v tem delu obravnavali vpliv osnovnih parametrov v enodimenzijskem modelu prenosa toplote. S tem bomo prikazali, kako optimirati prenos toplote in njegove učinke. Gostoto toplotnega toka v trdnini zaradi prevajanja toplote lahko opišemo z enačbo 2-1 [BAE12]. Temu ustrezno enačba 2-2 opisuje gostoto toplotnega toka zaradi konvekcije fluida [BAE12]. Oba člena se lahko po pravilu o ohranitvi energije izenačita. Tako se lahko neznana temperatura stene (T_{wall}) izloči, s čemer smo izpeljali enačbo 2-3. Oznake spremenljivk v enačbah 2-1 do 2-3 prikazuje slika 2-1. Enačba 2-3 je dobra osnova za razpravo o parametrih, ki imajo vpliv na toplotni tok. Tako slika 2-2 a-d ilustrira spreminjanje parametrov. Vsak diagram kaže spreminjanje ene spremenljivke; druge spremenljivke so pri tem konstantne.

Vidi se, da linearno povečanje toplotne prevodnosti povzroči eksponentno povečanje toplotnega toka. Orodna jekla za vroče preoblikovanje (npr. H11 ali H13) imajo navadno majhno toplotno prevodnost, kot prikazano na sliki 2-2a. Povečanje toplotne prevodnosti na vrednost 100 W/m.K občutno poveča toplotni tok.

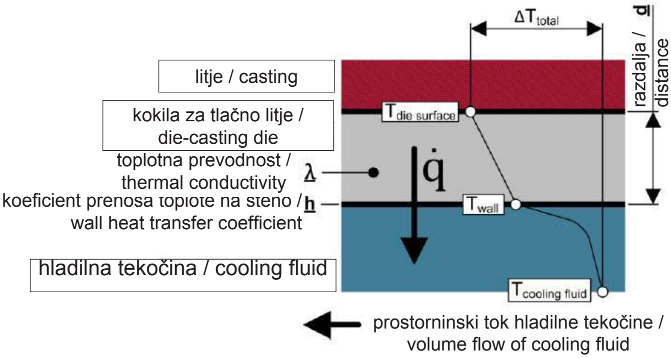
a negli-gible impact on the heat balance of the die, further challenges exist for the development of internal cooling systems.

In order to face the challenges mentioned above, a research project was conducted at the Institute of Joining and Welding. The solution strategy of the research project was split into two approaches: the optimization by a more efficient dimensioning of the cooling channels and the segmentation of the die in order to achieve conformal cooling channels.

2 Basics

2.1 Heat Transfer

Detailed information about the heat transfer between fluid and solid can be found in numerous sources [BAE12], [VDI06]. In order to focus on the main problem, only the influence of the basic parameters on a one-dimensional heat transfer model shall be considered in this section. This shall serve to point out the targets for a heat transfer optimization and its effects. The heat flux density in a solid due to heat conduction can be described according to equation 2-1 [BAE12]. Accordingly, equation 2-2 describes the heat flux density due to fluid convection [BAE12]. Both terms can be equated, based on the rule of energy conservation. Thus, the unknown wall temperature (T_{wall}) can be eliminated and equation 2-3 is derived. The designation of the variables for the equations 2-1 to 2-3 can be obtained from Figure 2-1. Hence, equation 2-3 is a good base for a discussion of the parameters that have an influence on the heat flux. For that purpose, Figure 2-2 a-d illustrates the variation of parameters. Each graph depicts the variation of one variable; the other variables were set constant.



$$\dot{q} = \frac{\lambda}{d}\left(T_{die\,surface} - T_{wall}\right)$$ enačba / Eg. 2-1

površina kokile / die surface
stena / wall
celoten / total

$$\dot{q} = h\left(T_{wall} - T_{cooling\,fluid}\right)$$ enačba / Eg. 2-2

$$\dot{q} = \frac{h \cdot \lambda}{\lambda + h \cdot d} \cdot \Delta T_{total}$$ enačba / Eg. 2-3

Slika 2-1. Shematični prikaz enodimenzijskega sistema toplotnega toka

Figure 2-1. Schematic description of a one-dimensional heat flux system

Vendar se učinek zmanjšuje z večjimi vrednostmi toplotne prevodnosti. V osnovi je toplotna prevodnost jekel za vroče preoblikovanje omejena iz metalurških vidikov. A če razdelimo kokilo za tlačno litje na segmente, je razumno uporabiti materiale z boljšo toplotno prevodnostjo. Vpliv koeficienta prenosa toplote na steno (slika 2-2b) kaže enako obnašanje kot toplotna prevodnost. Poleg tega se lahko ugotovi še dodatno pomembno dejstvo. Če pogledamo obliko krivulje, postane očitno, da mora biti glavni poudarek pri procesu načrtovanja na povprečnih vrednostih toplotnega prenosa.

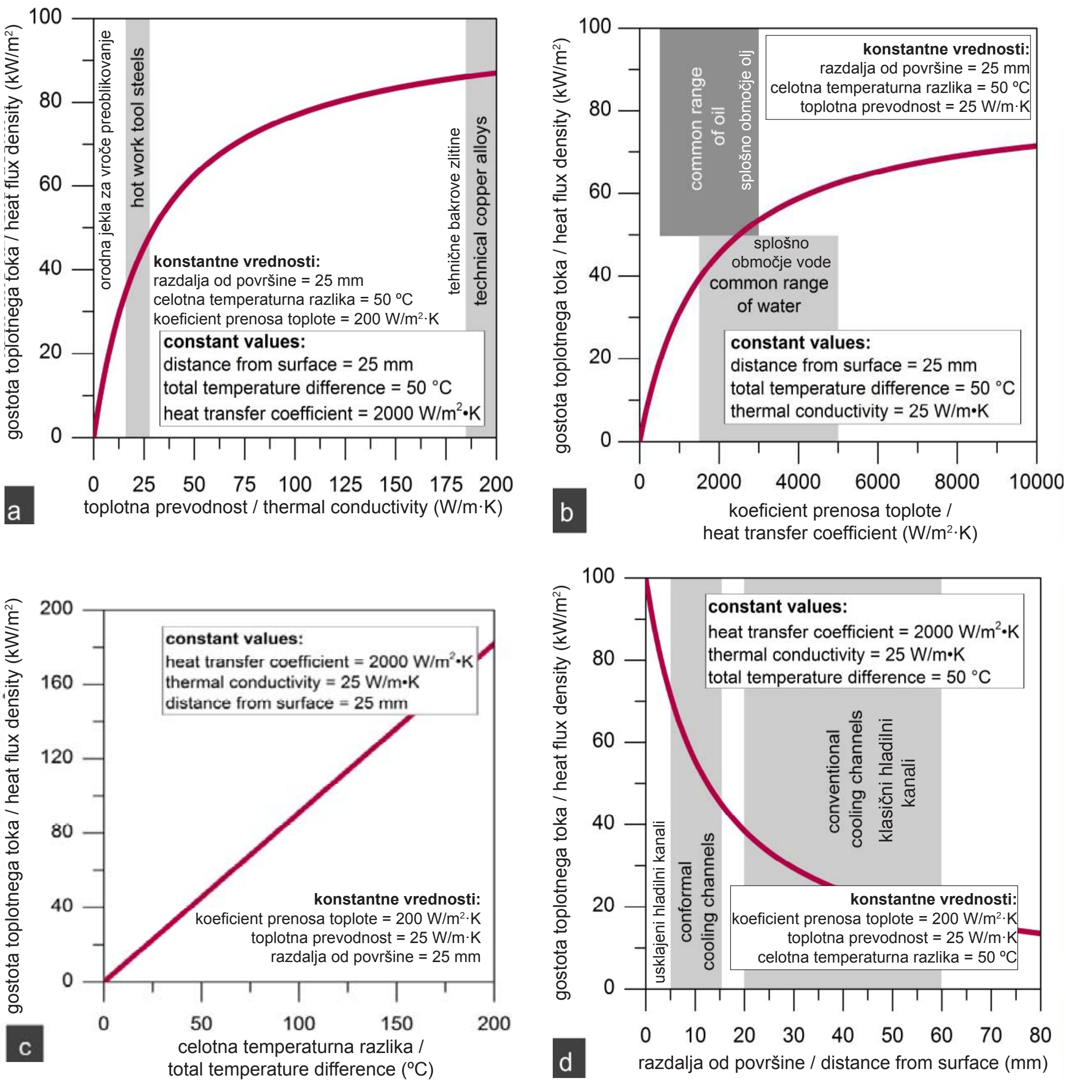
Nadaljnja optimiranja, kar se tiče prenosa toplote, bodo tudi povečala toplotni tok, vendar se bo njegov učinek občutno zmanjšal. Poleg tega se velike vrednosti koeficienta prenosa toplote na steno lahko dosežejo samo z velikimi hitrostmi toka. Vpliv temperaturne razlike se lahko ugotovi iz slike 2-2c. Kot se vidi, povzroča naraščajoče spreminjanje temperature ustrezno konstantno spreminjanja toplotnega toka. Zato je ustrezneje, da uporabljamo nizke temperature hladilnega sredstva. Poleg tega višja temperatura tudi povzroča večja napetostna nihanaj na površini. Glede na želeno daljšo življenjsko dobo materiala za

It becomes obvious that the effect of a linear increasing thermal conductivity results in an exponential increase of the heat flux. Hot work tool steels (e. g. H11 or H13) usually only possess a poor thermal conductivity as illustrated in Figure 2-2a. An increase of the thermal conductivity to a value of 100 W/m·K would enhance the heat flux significantly.

However, the impact decreases with higher values for the thermal conductivity. Basically, the thermal conductivity of hot work tool steels is restricted, due to metallurgical aspects. Nevertheless, in terms of the segmentation of a die-casting die, it is reasonable to use materials with a high thermal conductivity. The influence of the wall heat transfer coefficient (Figure 2-2b) exhibits an identical behaviour, com-pared to the thermal conductivity. In addition, further important information can be derived here. When examining the development of the graph, it becomes obvious that the main focus for the design pro-cess should be on ensuring the common values for the heat transfer.

Further optimizations regarding the heat transfer will also result in an increase of the heat flux, but the significance is substantially reduced. In addition to this tlačno litje se je treba temu na vsak način izogniti in zato ta parameter ni uporaben za optimiranje. Zadnji parameter, ki ga prikazuje slika 2-2d, je razdalja od površine kokile. Jasno se vidi, da zmanjšanje razdalje vodi do občutno večjega toplotnega toka zaradi eksponentne odvisnosti. To jasno potrjuje učinkovitost in uporabo

fact, high values for the wall heat transfer coef-ficient can only be obtained by very high values for the flow velocity. Information about the influence of the temperature difference can be derived from Figure 2.2c. As illustrated, increasing temperature changes lead to a corresponding constant change of the heat flux. Consequently, it is



Slika 2-2. Spreminjanje parametrov glede na enačbo 2-3

Figure 2-2: Variation of parameters according to equation 2-3 usklajenih hladilnih kanalov. Optimizacija tega parametra je omejena le z življenjsko dobo kokile, omejitvami pri konstruiranju (npr. pomanjkanje prostora) in posebnimi težavami, povezanimi z izdelavo.

Upoštevati je potrebno, da površina za menjavo toplote v tem primeru ni ovrednotena, ker delamo samo z enodimenzijskim modelom. Pri dvo- ali tridimenzijskih modelih je vpliv odvisen od velikosti in geometrije površin. Podatke o tem vplivu lahko najdemo v virih [BAE12], [VDI06]. Navadno povzroča večanje površin za menjavo toplote občutno večje toplotne tokove.

2.2 Zmanjšanje tlaka

Poglavje 2-1 je odkrilo, da je zelo pomembno ustvariti ustrezno hitrost toka v hladilnih kanalih, da bi se zagotovil dovolj velik koeficient prenosa toplote na steno. Vendar je tok skozi hladilne kanale povezan z zmanjšanjem tlaka. To zmanjšanje tlaka je posledica trenja ob stenah in trenjskih sil v hladilnem sredstvu [SIG12]. Slika 2-3 ilustrira to težavo za preprost sistem hladilnih kanalov v vložku kokile za tlačno litje. Enačbi 2-4 in 2-5 slonita na Bernouillijevi enačbi, z njima pa se zmanjšanje tlaka opisuje analitično [SIG12]. Da bi se dobilo preprosto rešitev, smo uporabili več predpostavk. Kot se lahko izpelje iz enačbe 2-6, se celotno zmanjšanje tlaka lahko razdeli na tri posamezne dele [NOG10].

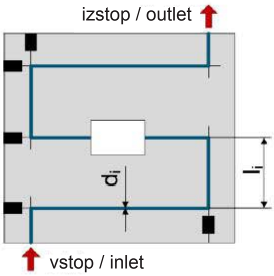
Enačba 2-7 opisuje, da je celotni koeficient trenja hladilnega sistema posledica treh delnih zmanjšanj tlaka [NOG10]. Celoten koeficient trenja je tudi posledica dveh mehanizmov: člen 1 opisuje vpliv koeficienta trenja ob steni; člen 2 opisuje koeficient trenja kot posledico ovir (npr. sprememba smeri ali hladilni elementi) v območju toka. Primer je prikazan na sliki 2-3, kjer celoten koeficient trenja določa

eligible to oper-ate with low temperatures of the cooling fluid. However, a higher temperature difference also leads to larger stress amplitudes at the die surface. With respect to a high lifetime of the die-casting material, this should be avoided by all means and therefore this parameter is not applicable for the optimization. The last parameter illustrated in Figure 2-2d is the distance from the die surface. As it can be seen clearly, a decrease of the distance leads to a substantial higher heat flux due to an exponential corre-lation. This clearly substantiates the effectiveness and application of conformal cooling channels. The optimization of this parameter is limited only by restrictions due to the lifetime of the die, design re-strictions (e. g. a lack of space) and especially problems associated with production.

Note that the area of the heat exchanging surface is not evaluated in this example since this is only a one-dimensional model. For two or three-dimensional models, the influence depends on the surface area and the geometry of the surfaces. Information about this influence can be found in the literature [BAE12], [VDI06]. Usually, an increase of heat exchanging surfaces also leads to a significantly higher heat flow.

2.2 Pressure Drop

Chapter 2.1 revealed that it is essential to establish an adequate flow velocity in the cooling channels in order to ensure a sufficient wall heat transfer coefficient. However, a pressure drop results from the flow through the cooling channels. This pressure drop originates from the wall friction and frictional forces within the cooling fluid [SIG12]. Figure 2-3 shall serve to illustrate this issue for a simple cooling channel system in a die-casting die insert. The equations 2.4 and 2.5 are based on Bernoulli's princi-ple and are used to



$$z_{in} \cdot g + \frac{p_{in}}{\rho_{in}} + \frac{u_{in}^2}{2} = z_{out} \cdot g + \frac{p_{out}}{\rho_{out}} + \frac{u_{out}^2}{2} + Y_{L,12}$$ enačba / Eg. 2-4

$u_{in} = u_{out} = u$
$\rho_{in} = \rho_{out} = \rho$
$z_{in}, z_{out} = 0$ yield

Yield - izkoristek
Cooling lines - hladilni kanali
Redirections - spremembe smeri
Cooling element - hladilni elementi

$$p_{in} - p_{out} = \Delta p = Y_{L,12} \cdot \rho$$ enačba / Eg. 2-5

$$Y_{L,12} = \left(\zeta_{\text{cooling lines}} + \zeta_{\text{redirections}} + \zeta_{\text{cooling elements}}\right) \cdot \frac{u^2}{2} = \zeta_t \cdot \frac{u^2}{2}$$ enačba / Eg. 2-6

Slika 2-3. Shematičen prikaz toka fluida in različnih odporov toku

Figure 2-3. Schematic description of a one-dimensional heat flux system

specifična površina hladilnega sistema, premer izvrtine, podatek o hrapavosti površine in specifični koeficient trenja za en hladilni element ter šest sprememb smeri.

$$\zeta_t = \underbrace{\lambda_i \cdot \frac{l_i}{d_i}}_{\text{člen 1 / term 1}} + \underbrace{\sum_{k=1}^{n} \zeta \cdot \frac{A_{ind}^2}{A_{ref}^2}}_{\text{člen 2 / term 2}}$$ enačba / Eg. 2-7

kjer je

λ_i	koeficient trenja ob steni
l_i	skupna dolžina hladilnega kanala
d_i	premer izvrtine
A_{ref}	primerjalni prerez za izračun koeficienta trenja
A_{ind}	posamezni primerjalni prerez hladilnega elementa

Narejene so bile obsežne raziskave, da bi se lahko opisal koeficient trenja ob steni, podatki pa se lahko najdejo v literaturi [LAU09], [SIG12]. Enako velja za spremembe smeri toka v kokili za tlačno litje [NOG10], [MEN99], [VDI06], čeprav preiskane geometrije često komaj ustrezajo geometriji v kokili za tlačno litje (geometrija, ki je posledica križanja dveh izvrtin). Glavni poudarek bo dan hladilnim elementom, ker ti elementi navadno povzročajo največje zmanjšanje tlaka in zato zahtevajo natančno ovrednotenje. Vrednost koeficienta trenja

describe the pressure drop analytically [SIG12]. In order to retrieve a straightforward solution, several assumptions were made. As it can be derived from equation 2.6, the pressure drop is divided into three individual losses [NOG10].

Equation 2-7 describes the total friction factor of the cooling system that originates from the three losses [NOG10]. The total friction factor results from two different mechanisms: Term 1 describes the influence of the wall friction factor; Term 2 describes a friction factor that originates from obstacles (e. g. redirections or cooling elements) in the flow passage region. For the example given in Figure 2-3, the total friction factor is determined by a specific length of the cooling system, the diame-ter of the bore, information about the surface roughness and by a specific friction factor for one cooling element and six redirections.

λ_i	wall friction factor
l_i	accumulated length of the cooling channel
d_i	bore diameter
A_{ref}	reference cross section of the calculated friction factor
A_{ind}	individual reference cross section of the cooling element

Extensive research has been conducted in order to describe the wall friction so za hladilni element mora biti odvisna od hitrosti toka. Ker hitrost toka v hladilnem elementu ni konstantna zaradi različnim prerezov, prerez primerjalnega premera nudi enak odpor kot celoten sistem odporov (v našem primeru Aind). Enačba 2-8, ki sledi, opisuje izračun koeficienta trenja in izkoristke iz preje omenjenih enačb 2-5 in 2-6. Ta enačba se uporablja, da pretvori rezultate izračuna zmanjšanja tlaka, ki smo jih dobili s preskusi in numeričnimi izračuni, v koeficient trenja. Ker hitrost toka znotraj hladilnega elementa ni konstantna, se uporabi primerjalna hitrost (ki se dobi na osnovi primerjalnega prereza). Ustrezna vrednost tega prereza bi bil prerez ostalih hladilnih kanalov, ki so izdelani z orodjem za globoko vrtanje izvrtin.

$$\zeta = \frac{\Delta p}{\frac{\rho}{2} \cdot u^2}$$ enačba / Eg. 2-8

kjer je

Δp	tlačna razlika med vstopom in izstopom
ρ	gostota fluida za hlajenje/prenos toplote
u	hitrost fluida za hlajenje/prenos toplote

3 CFD-izračun parametrov hladilnega sistema

Da bi dobili ustrezno zanesljive parametre, je bilo treba upoštevati naslednje pomembne vidike [ANS10b]:

- podrobno modeliranje geometrije hladilnega kanala,
- skrbna izbira modela fluida (npr. turbulenčnega modela),
- združitev primernih lastnosti materiala in
- izbira ustreznih robnih pogojev.

Za analizo je bila uporabljena računalniška oprema ANSYS CFX. Prvi

that further information can be found in the literature [LAU09], [SIG12]. The same applies to the redirections in the die-casting die [NOG10] [MEN99] [VDI06], although the examined geometries often hardly correspond to the ge-ometry that exists in the die-casting die (a geometry that results from the crossing of two bores). The main emphasis shall be put on the cooling elements since the elements usually induce the highest pressure drop and hence require a precise evaluation. The value of the friction factor for the cooling element must be referred to a flow velocity. Since the flow velocity within the cooling element is not constant due to different profiles, the cross section of a reference diameter is integrated (here: Aind).

The equation 2.8 stated below describes the calculation of the friction factor and yields from the equa-tions 2.5 and 2.6, mentioned above. This equation is used to transform the pressure drop results, de-rived from experimental and numerical investigations, to a friction factor. Since the flow velocity inside of the cooling element is not constant, a reference velocity (which results from a reference cross sec-tion) has to be used here. A reasonable value for this cross section would be the cross section of the remaining cooling channels that are manufactured by deep hole drilling tools.

Δp	pressure difference between inlet and
ρ	outlet density of the cooling/ heat transfer
u	fluid velocity of the cooling/ heat transfer fluid

3 CFD-BASED EVALUTION OF COOLING SYSTEM PARAMETERS

In order to retrieve reliable results, the following major aspects necessarily should be considered [ANS10b]:

- the detailed modeling of the cooling

korak je modeliranje geometrije hladilnega kanala. Ker to zahteva izračun prenosa toplote na steno, sta bili modelirani dve območji: območje fluida (geometrija hladilnega kanala) in območje trdnine (kokila za tlačno litje). Materialne lastnosti materiala, odvisne od temperature, se lahko dobe za večino hladilnih tekočin in so bile integrirane v simulacijo. Ker se hladilne tekočine navadno uporabljajo v sorazmerno ozkem temperaturnem območju, so se za določene simulacije uporabile konstantne materialne vrednosti.

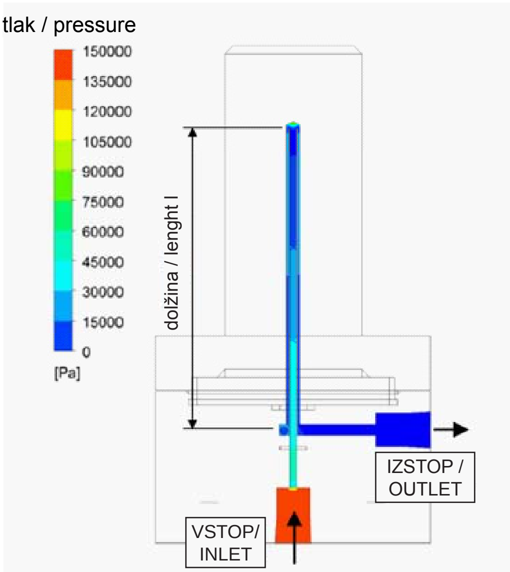
Večina preiskanih tokov je turbulentnih [SIG12], [NOG10]. Raje pa imamo za naš namen stacionarne simulacije, ker so krajše, naknadna obdelava je preprostejša, navadno pa nas zanimajo povprečne časovne vrednosti [EGG11]. Zato smo uporabili Reynolds-povprečni Navier-Stokesov model (RANS – Reynolds-Averaged Navier-Stokes (op.prevajalca)) in strižno-napetostni model prenosa (SST) kot turbulenčni model. Ta model združuje prednosti k-ε modela in k-ω modela ter se lahko obravnava kot industrijski standard za modeliranje turbulence, ker so ga številne aplikacije verificirale, njegovo delovanje je robustno za večino mrežnih topologij, ima dobro interoperabilnost z drugimi fizikalnimi modeli in prefinjeno obravnava steno [EGG11]. Pri vseh izračunih smo uporabili robne pogoje brez zdrsa. Hitrost fluida je ob steni nič, kar je dober približek realnemu toku fluida. Da bi bil izračun koeficienta prenosa toplote na steno zaupanja vreden, je bilo treba skrbno paziti na modeliranje mejnih plasti. Zato je bilo treba zagotoviti, da so bili hitrostni profil fluida in pojavi prenosa energije v območju sten pravilno modelirani [ANS10a], [ANS10b].

Slika 3-1 prikazuje tipični rezultat za zmanjšanje tlaka pri kaskadnem spoju vodnih kanalov s premerom izvrtine 5 mm. Kot robni pogoj je bilo postavljeno, da je

channel geometry,
- the careful selection of the fluid model (e. g. the turbulence model),
- the integration of suitable material properties and
- the selection of reasonable boundary conditions.

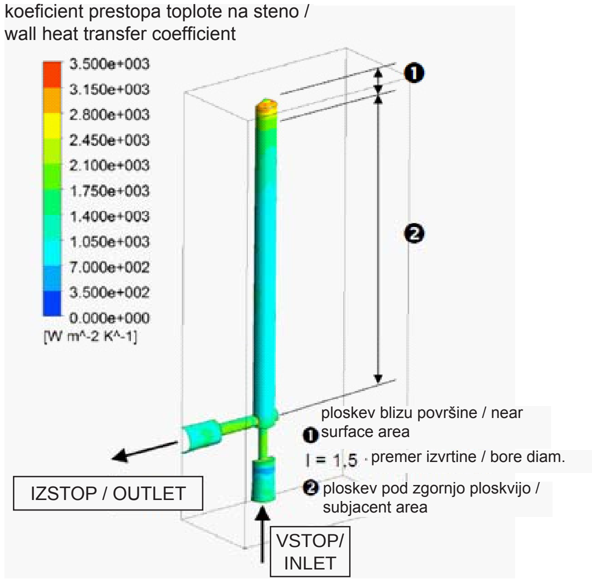
The analyses were carried out by the software ANSYS CFX. The first step is the modeling of the cooling channel geometry. Since it is required for the calculation of the wall heat transfer, two domains are modeled: the fluid domain (the cooling channel geometry) and the solid domain (the die-casting die). Temperature dependent material properties of the major cooling fluids are accessible and were inte-grated into the simulation. Since the cooling fluid is usually operated at a rather narrow temperature range, constant material properties were used for a specific simulation setup.

The majority of examined flows are turbulent [SIG12], [NOG10]. Steady state simulations are preferred for this application because they exhibit a shorter simulation time, post-processing is simplified and usually only time-averaged values are of interest [EGG11]. Hence, a Reynolds-Averaged Navier-Stokes model (RANS) is applied. Accordingly, the Shear-Stress-Transport model (SST) was selected as a turbulence model. This model combines the advantages of the k-ε mo an th k -ω mo an can be regarded as an industrial standard for turbulence modeling since it has been validated for a broad range of applications, shows a robust performance on most of the mesh topologies, has a good interoperability with other physical models and exhibits a sophisticated treatment of the wall [EGG11]. For all of the conducted calculations, a *no-slip* boundary condition was applied. The fluid will have zero velocity relative to the boundary which is a good



Slika 3-1. Zmanjšanje tlaka zaradi toka fluida pri kaskadnem spoju vodnih kanalov (hladilna tekočina: voda, povprečna temperatura: 50 °C, premer izvrtine: 5 mm, hitrost toka na vstopu: 2,5 l/min)

Figure 3-1. Pressure drop due to a fluid flow in a cascade water junction (cooling fluid: water, averaged temperature: 50 °C, bore diameter: 5 mm, flow velocity at the inlet: 2,5 l/min



Slika 3-2 Koeficient prenosa toplote na stene v odvisnosti od geometrije stene pri kaskadnem spoju vodnih kanalov (hladilna tekočina: voda, povprečna temperatura: 50 oC, premer izvrtine: 12 mm, hitrost toka na vstopu: 20,5 l/min)

Figure 3-2. Geometry dependent wall heat transfer coefficient of a cascade water junction (cooling fluid: water, inlet temperature: 50 °C, bore diameter: 12 mm, flow velocity at the inlet: 20,5 l/min)

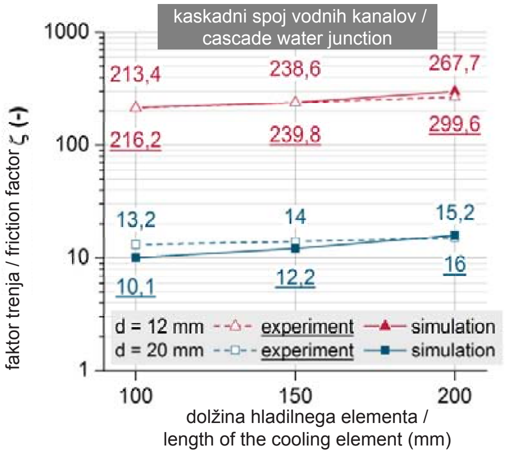
hitrost toka na vstopu konstantna in da ima tlak na izstopu vrednost atmosferskega tlaka (1 bar).

Razlika tlakov je bila izračunana iz razlike med tlakom na vstopu in tlakom na izstopu, v našem primeru pa je bila okoli 1,3 bar. Ker je za izračun potrebno le celotno zmanjšanje tlakov hladilnega elementa, ni pomembno vrednotenje lokalnih površin. Slika 3-2 prikazuje porazdelitev koeficienta prenosa toplote na steno. Zapomnimo si, da je prenos toplote funkcija Reynoldsovega števila in geometrije ter temperaturne razlike sistema ($T_{stena}/T_{hladilni\ fluid}$). Zato ni uresničljivo ugotoviti samo eno vrednost za koeficient prenosa toplote na steno, ampak

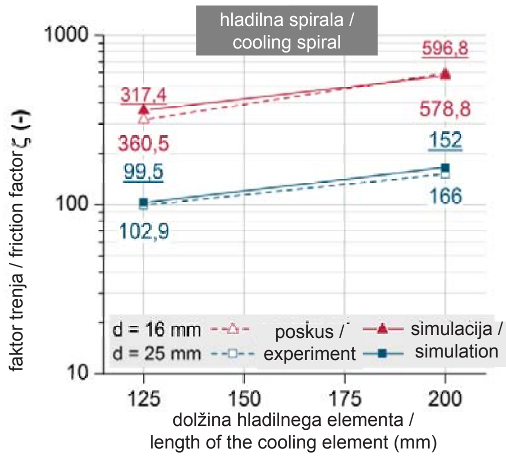
approximation of the real fluid flow. In order to calcu-late a trustworthy wall heat transfer coefficient, the modeling of the boundary layers has to be carefully attended to. Thereby, it is ensured that the velocity profile of the fluid and the energy transport phe-nomena at the wall regions are modeled correctly [ANS10a], [ANS10b].

Figure 3-1 exemplarily shows the result for the pressure drop in a cascade water junction with a bore diameter of 5 mm. As a boundary condition, the flow velocity at the inlet was set to constant and pres-sure at the outlet was set to atmospheric pressure (1 bar).

primerjava faktorja trenja – eksperimentalni in računski rezultati /
comparison of the friction factor – experimental and numerical results



primerjalni / reference Ø: 10 mm



Slika 3-3. Primerjava faktorjev trenja za različne kaskadne spoje vodnih kanalov, ugotovljenih eksperimentalno in z CFD-simulacijami

Figure 3-3. Comparison of friction factors for various cascade water junctions, determined by experimental measurements and CFD simulations

Slika 3-4. Primerjava faktorjev trenja za različne hladilne spirale, ugotovljenih eksperimentalno in z CFD-simulacijami

Figure 3-4. Comparison of friction factors for various cooling spirals, determined by experimental measurements and CFD simulations

številsko rešitev za celotni hladilni element. Da bi se poenostavil vpliv geometrije, sta bili definirani dve območji: ploskev blizu površine (1) in ploskev tik pod njo (2). Potem so se ugotovile povprečne vrednosti koeficienta prenosa toplote na steno za vsako območje. Zaradi omejitev modela, prikazanih na sliki 3-2, so bili izračunani koeficienti prenosa toplote na steno med 3000 W/m^2 K (blizu površine kokile) in 1000 W/m^2 K (na spodaj ležečih ploskvah).

Rezultati izračunanih faktorjev trenja so bili eksperimentalno preverjeni. Zaradi industrijske pomembnosti so bili preiskani različni kaskadni spoji vodnih kanalov in hladilnih spiral. V tem kontekstu kažeta dobljene rezultate sliki 3-3 in 3-4. Iz obeh diagramov se vidi, da je odstopanje med izračunanimi in eksperimentalnimi rezultati zanemarljivo majhno glede na stopnjo natančnosti, ki je želena pri tehničnem

The pressure difference is calculated from the pressure difference at the inlet and at the outlet, in this case the pressure drop is about 1.3 bar. Since only the total pressure drop of a cooling element is necessary for a calculation, the evaluation of local areas is not relevant. Figure 3-2 illustrates the dis-tribution of the wall heat transfer coefficient. Note that the heat transfer is a function of the Reynolds number, the geometry and the temperature difference of the system ($T_{wall}/T_{cooling\ fluid}$). Hence, it is not feasible to determine only one parameter for the wall heat transfer coefficient but a parametric solution for a cooling element. In order to simplify the influence of the geometry, two areas were defined: the near surface area (❶) and the subjacent area (❷). Afterwards, the results for the wall heat transfer coefficient were averaged for each area. For the konstruiranju. V nadaljevanju ni bilo sistematičnih odstopanj. Ker je bila ta stopnja ujemanja dosežena pri različnih geometrijah in velikostih hladilnih elementov, predlagamo, da se metoda računanja lahko prenese tudi na druge hladilne geometrije.

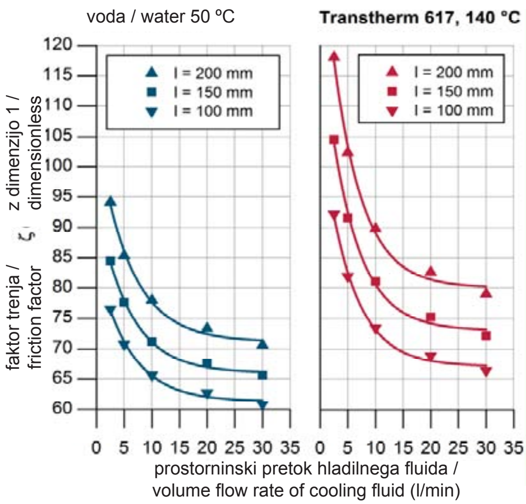
Poleg tega smo naredili poskuse, da bi preverili izračunane vrednosti koeficienta prenosa toplote na steno. V tem primeru so bile izračunane vrednosti tudi preverjene (ni prikazano tukaj). Vendar smo opazili majhno sistematično odstopanje med računskimi in eksperimentalnimi rezultati: izračunani koeficient prenosa toplote na steno je bil večji od izmerjene vrednosti za faktor 1,05 – 1,10. Vzrok za to se lahko najde v dejstvu, da numerična simulacija predpostavlja idealno steno brez onesnaženja na mejni površini. Kljub temu se lahko razume, da so izračunane vrednosti dovolj zanesljive glede na stopnjo natančnosti, ki je potrebna za tehnično konstruiranje, in se zato lahko uporabijo v procesu konstruiranja. Slika 3-5 kaže rezultate 30 izračunov za ugotavljanje faktorja trenja za kaskadne spoje vodnih kanalov različnih dolžin (prim. sliko 3-1). Uporabljena enota na x-osi je bila l/min, ker se ta navadno uporablja v livarnah in pri enotah za krmiljenje temperature. Izpelje se lahko iz dejstva, da faktor trenja ni konstantna vrednost ampak funkcija pretoka hladilnega fluida. Uporablja se predvsem za majhne hitrosti tokov. Daljši kaskadni spoji vodnih kanalov povzročajo večja zmanjšanja tlaka. Zato imajo ti elementi večji faktor trenja. Računali smo z dvema vrstama fluidov: vodo z materialnimi lastnostmi fluida pri 50 ^{o}C in fluidom TRANSTHERM 617 za prenos toplote z materialnimi lastnostmi fluida pri 140 ^{o}C (prim. [MAR06] s primerljivimi lastnostmi fluida). Izbirali smo na osnovi dejstva, da je med obema fluidoma razmeroma velika razlika viskoznosti in zaradi tega imata različne faktorje trenja. Izbira več materialov bi bila prezapletena

model constraints described in Figure 3-2, wall heat transfer coefficients from 3000 W/(m^{2}K) (at the near surface areas) and 1000 W/m^{2}K (at the subjacent areas) were calculated.

The results for the calculated friction factor were validated by experimental investigations. Due to its industrial relevance, various water cascade junctions and cooling spirals were examined. In this con-text, Figures 3-3 and 3-4 display the achieved results. It can be taken from both diagrams that the deviation of the numeric results and the experimental results is negligible in respect of a degree of accuracy that is desirable for engineering design. Furthermore, there is no systematic deviation. Since this degree of accordance was achieved for various cooling element geometries and sizes, it was sug-gested that the calculation method can be transferred to further cooling geometries.

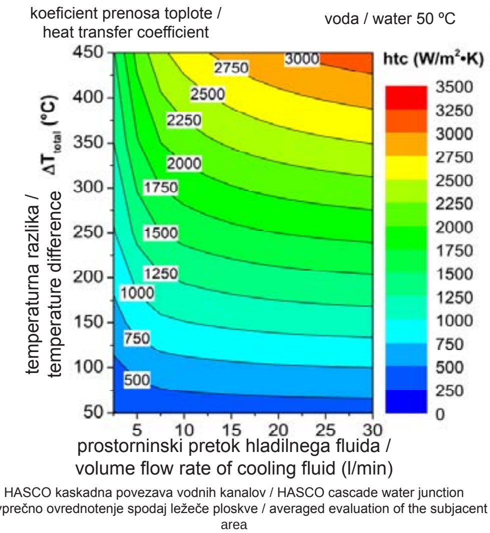
Moreover, experimental research was conducted in order to verify the calculated results for the wall heat transfer coefficient. In this case, the calculated results also were verified (not illustrated here). However, a slight systematic deviation was observed between the numeric and the experimental re-sults: the calculated wall heat transfer coefficient exceeded the measured value by the factor 1,05 -1,10. The reason for this deviation can be found in the fact that the numeric simulation assumes an ideal wall without any contaminations at the boundary surface. Nevertheless, the calculated results for the wall heat transfer coefficient can be regarded as trustworthy in a respect of a degree of correct-ness that is worthwhile for engineering design and therefore can be used for the design process.

Figure 3-5 displays the results of 30 calculations for determining the friction factor of a cascade water junction with various lengths (c. f. Figure 3-1). The unit



Slika 3-5. Izračunani faktorji trenja v odvisnosti od pretoka fluida pri kaskadnem spoju vodnih kanalov, primerjalni premer je 16 mm

Figure 3-5. Calculated friction factor due to fluid flow in a cascade water junction; reference diameter is 16 mm



Slika 3-6. Izračunani koeficienti prenosa toplote na steno pri kaskadni povezavi vodnih kanalov (spodaj ležeče ploskve)

Figure 3-6. Calculated wall heat transfer coefficient in a cascade water junction (subjacent areas

za obdelovanje, ker vsaka krivulja zahteva več računanj. Diagram na sliki 3-5 omogoča uporabniku z vidika celotnega zmanjšanja tlaka izbiro med dvema fluidoma. *Voda pri 50 °C* naj bi se izbrala, če se uporablja voda ali hladilni fluid na osnovi vode (v kateremkoli temperaturnem območju). Rezultati z *TRANSTHERM 617* so uporabni, kadar se uporablja fluid za prenos toplote pri razmeroma nizki temperaturi (100-160 °C).

Slika 3-6 kaže izračunane koeficiente prenosa toplote na steno hladilnega elementa kot funkcijo temperaturne razlike in prostorninskega pretoka. Uporabili smo dvodimenzijske interpolacije ter funkcijo za glajenje krivulje, da bi ponazorili rezultate numeričnih izračunov. Slika 3-6 velja za vodo kot hladilno sredstvo in se nanaša na spodnjo plast (prim. sliko 3-2). Tu je koeficient prenosa toplote na

of the x-ax s was s t to “ /m n” since its use is common in foundries and temperature control units. It can be derived from that the friction factor is not a constant value but a function of the cooling fluid flow rate. This especially applies for low values of the flow velocity. Longer water cascade junctions cause a higher pressure drop. Hence, these ele-ments exhibit an increased friction factor. The calculations were done for two fluids: water with fluid material properties that correspond to a temperature of 50 °C and TRANSTHERM 617 heat transfer fluid with fluid material properties that correspond to a temperature of 140 °C (cf. [MAR06] with comparable fluid properties). The selection is founded on the fact that both fluids exhibit a relatively high difference˝in the viscosity and thus exhibit different friction factors. The selection of more materials would be too complex to handle since every graph needs steno eksponentna funkcija pretoka (in s tem tudi Reynoldsovega števila). Vpliv prostorninskega pretoka je pomemben pri majhnih pretokih in se manjša, ko se povečuje pretok. Poleg tega spreminjanje temperaturne razlike vodi do ustrezne konstantne spremembe koeficienta prenosa toplote na steno (glede na sliko 2-2c). Na tej sliki je temperaturna razlika ΔT_{total} izračunana iz povprečne temperature kokile (na oddaljeni točki, kjer ni neposrednega vpliva hladilnega elementa) in povprečne temperature hladilnega sredstva. Nadaljnji izračuni bodo dali vrednost na določeni razdalji od hladilnega elementa. S tem bo lahko uporabnik pri simulaciji litja (npr. MAGNASOFT) uporabil temperaturno odvisni koeficient za prenos toplote na steno.

4. Izvedba optimiranega hladilnega sistema

Dobljeni rezultati so nas opogumili, da uporabimo metode računanja za obstoječi kokilni vložek kokile za tlačno litje. Zato je bilo treba preiskati možnost optimiranja toplotnega toka za vso kokilo za tlačno litje. Uporabili smo dve metodi načrtovanja, da bi se povečal toplotni tok: optimalno mesto klasičnih hladilnih elementov in uporaba strategije delitve na segmente. Zato slike 4-1a do 4-1c predstavljajo konstrukcije hladilnih kanalov.

Slika 4-1a kaže začetno konstrukcijo hladilnih kanalov, izdelanih z globokim vrtanjem izvrtin. Po ovrednotenju te konstrukcije smo izračunali različne optimizacije. Končna konstrukcija optimizacije s klasičnimi hladilnimi elementi (vzporedna/serijska vezava odbojnih elementov) je prikazana na sliki 4-1b. Nazadnje slika 4-1c prikazuje obrise uporabljenega segmenta. V tem primeru

several calculations. In terms of the total pressure drop, the diagram shown in Figure 3-5 enables the user to select between two fluids. Water 50 °C should be selected if water or water-based cooling fluid (at any temperature range) is used. The results of TRANSTHERM 617 are applicable if a heat transfer fluid is used with a comparatively low temperature (100-160 °C).

Figure 3-6 displays the calculated wall heat transfer coefficient of the cooling element as a function of the temperature difference and the volume flow rate. A two-dimensional interpolation and a smoothing function were used in order to illustrate the results of numerous calculations. The Figure 3-6 is valid for water as a cooling fluid and corresponds to the subjacent area (cf. Figure 3-2). Here, the wall heat transfer coefficient is an exponential function of the flow rate (and thus the Reynolds number). The influence of the volume flow rate is significant at low values of the flow rate and reduces with an in-crease of the flow rate. Moreover, a change in the temperature difference leads to a corresponding constant change of the wall heat transfer coefficient (according to Figure 2-2c). In this Figure, the tem-perature differ nc ΔT total originates from the average temperature of the die (at a remote point which is not influenced directly by the cooling element) and the average temperature of the cooling medium.

Further calculations will display the value for a defined distance from the cooling element. Thereby, the user is enabled to implement a temperature dependent wall heat transfer coefficient in the casting simulation (for instance MAGMASOFT).

4 Implementation of an Optimized Cooling System

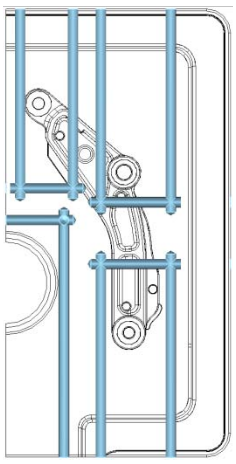
The achieved results encouraged to apply the calculation methods to an existing die-je območje hlajenja 7,5 mm pod površino livne votline, vstopna in izstopna odprtina sta integrirani v segment, zato nista vidni.

Slike 4-2a do 4-2c kažejo rezultate pretoka fluida in pojasnjujejo izboljšanje toplotnega izkoristka kokile za tlačno litje. V tem primeru je bila kokila za tlačno litje (materialne lastnosti so ustrezale orodnemu jeklu za vroče preoblikovanje H11) nastavljena na začetno temperaturo 400 °C. Temperatura hladilne vode je bila nastavljena na 50 °C in hitrost toka na 20 l/min. Po 60 s delovanja je bila izračunana srednja temperatura površine livne votline. Ta model bo uporabljen za ugotavljanje delovanja hladilnih sistemov pri odvajanju velike količine toplote.

casting die insert. Hence, the potential to optimize the heat flux of the whole die-casting die ought to be examined. Two design methods were used in order to increase the heat flux: the optimized allocation of conventional cooling elements and the application of segmentation strategies. For this reason, Figure 4-1a to Figure 4-1c display the design of the cooling channels.

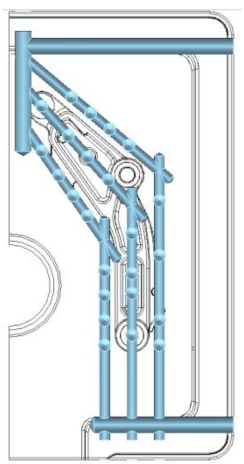
Figure 4-1a shows the initial design of the cooling channels, manufactured by deep hole drilling. After the assessment of this design, various optimizations were calculated. The final design of an optimiza-tion with conventional cooling elements (a parallel/series connection of baffle elements) is illustrated in Figure 4-1b. Finally, Figure 4-1c shows the contour of the applied die segment. In this case, the cool-ing area is located 7,5 mm beneath the surface of the cavity, the inlet and outlet is integrated into the segment, hence it is not visible here.

Figure 4-2a to Figure 4-2c display the results of a transient fluid simulation and clarify the enhance-ments in the thermal output of the die-casting die. Here, the die-casting die (material properties corre-spond to a H11 hot work tool steel) was set to an initial temperature of 400 °C. The temperature of the cooling fluid water was set to 50 °C and the flow



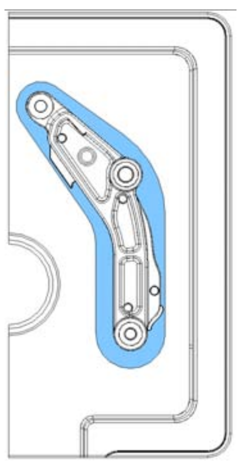
Slika 4-1a. Začetna konstrukcija hladilnih kanalov

Figure 4-1a. Initial design of the cooling channels



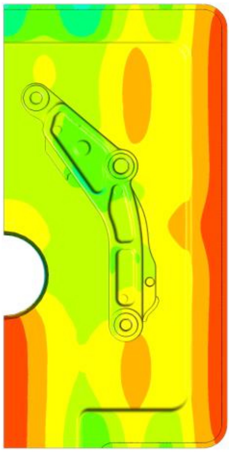
Slika 4-1b. Optimirana konstrukcija klasičnih hladilnih elementov

Figure 4-1b. Optimized design of conventional cooling elements



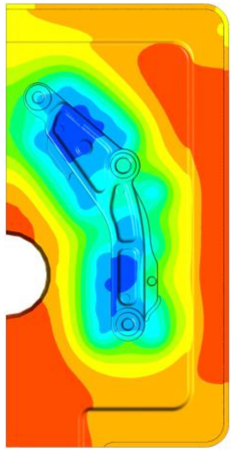
Slika 4-1c. Delitev kokilnega vložka na segmente, usklajeni hladilni kanali

Figure 4-1c. Segmentation of the die insert, conformal cooling channels



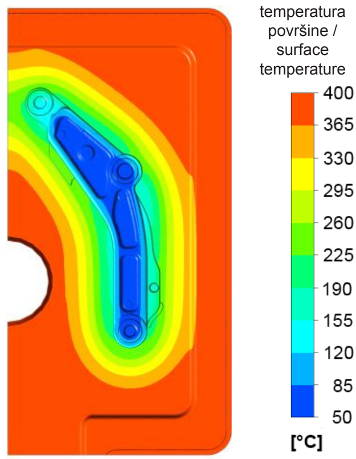
Slika 4-2a. Povprečna temperatura na površini livne votline kokile: 305 °C

Figure 4-2a. Average temperature at the cavity surface of the die: 305 °C



Slika 4-2b. Povprečna temperatura na površini livne votline kokile: 124 °C

Figure 4-2b. Average temperature at the cavity surface of the die: 124 °C



Slika 4-2c. Povprečna temperatura na površini livne votline kokile: 69 °C

Figure 4-2c. Average temperature at the cavity surface of the die: 69 °C

5 Povzetek in sklepi

Prispevek opisuje glavne vplivne parametre za optimizacijo odvajanja toplote iz kokile za tlačno litje. Pokazano je bilo, da sta razdalja od površine livne votline in koeficient prenosa toplote na steno bistvena parametra, da se izboljša odvajanje toplote iz kokile za tlačno litje. Da se doseže zanesljive vrednosti koeficienta za prenos toplote na steno, je potrebno poznati hitrost toka fluida za prenos toplote. Zato so bile opisane metode za računanje faktorja trenja hladilnih elementov s trgovsko CFD-računalniško opremo, imenovano ANSYS CFX. Izračunani rezultati so se primerjali z rezultati poskusov in ugotovljeno je bilo dobro ujemanje. Poleg tega je bila uporabljena metoda končnih elementov za modeliranje prenosa toplote med fluidom za odvajanje toplote in kokilo za tlačno litje.

velocity was set to 20 l/min. After a runtime of 60 s, the mean temperature at the cavity surface was evaluated. Hence, this model shall serve to determine the performance of the cooling systems in respect to a high heat output.

5 Summary and Conculsions

The article described the major influencing parameters for a heat output optimization of the die-casting die. It was pointed out that the distance from the cavity surface and the wall heat transfer coefficient are essential parameters in order to increase the heat output of the die-casting die. In order to achieve reliable values for the wall heat transfer coefficient, it is necessary to know the flow velocity of the heat transfer fluid. In this context, methods to calculate

Znova je bilo ugotovljeno dobro ujemanje med obema metodama. Predloženo je bilo, kako se lahko oba značilna parametra pretvori v tehnične specifikacije.

Končno je bil opisan izračun prenosa toplote za celotno kokilo za tlačno litje. Ta simulacija prikazuje učinkovitost optimizacije. Lahko se vidi, da obstaja določena možnost optimiranja klasičnih hladilnih sistemov. Vendar uporaba kokilnih vložkov, razdeljenih na segmente, da bi se prišlo do usklajenih hladilnih kanalov, celo presega zmožnost klasičnih hladilnih sistemov zaradi manj omejitev glede na površino za menjavo toplote in razdaljo do površine. Zato je vredno nadaljevati z razvijanjem usklajenih hladilnih kanalov z delitvijo kokile za tlačno litje na segmente.

Zaradi izboljšav CFD-modelov, ki so v teku, se zdi, da je možno izvesti izboljšave učinkovitosti sistemov za reševanje in delovanja računalniških enot ter uporabe CFD-analize ter je smiselna izboljšava procesov konstruiranja kokil za tlačno litje. Trenutno smo ugotovili omejitve pri celotnem procesu modeliranja, ker je še vedno zelo zamuden.

Tehnične specifikacije, opisane v tem prispevku, bodo skrajšale ta postopek konstruiranja. Za veliko število kokil za tlačno litje je lahko ta metoda smiselna strategija. Vendar so hladilni kanali v obstoječih kokilah za tlačno litje često veliko preveč kompleksni, da bi prišli do rezultatov samo s temi tehničnimi specifikacijami. Enako velja za usklajene hladilne kanale, do katerih se pride s strategijami delitve na segmente ali z dodatno izdelanimi kanali. Zato je zaželeno, da se pri procesu konstruiranja uporabi celotna izvedba in se s tem pride do natančnega poznavanja porazdelitve temperature.

the friction factor of cooling elements with the com-mercial CFD software Ansys Cfx were described. The calculated results were compared to the results from experimental investigations and a good accordance has been found. Furthermore, the finite element code was used to model the heat transfer between the heat transfer fluid and the die-casting die. Reasonable accordance between both methods was found again. It was suggested how both characteristic parameter can be transformed into engineering specifications.

Finally, the calculation of the heat transfer within an entire die-casting die was depicted. This simula-tion illustrated the efficiency of the optimization. It could be shown that there is a considerable potential to optimize conventional cooling systems. However, the application of segmented die inserts in order to achieve conformal cooling channels even excels the capacity of conventional cooling systems due to fewer restrictions in regard to the heat exchanging surface and surface distance. Hence, it is worth-while to establish and to advance the development of conformal cooling channels by the segmentation of die-casting dies.

Due to an ongoing enhancement of the CFD models, improvements in the efficiency of the solvers and in the performance of computing units, the utilization of the CFD analysis appears to be feasible and reasonable to enhance the design process of die-casting dies. At this time, the restrictions are founded on the whole modeling process which still can be regarded as very time-consuming.

The engineering specifications described in this article shall serve to shorten this design process. For a large number of die-casting dies, this method is might be a sensible strategy. However, cooling channels of existing die-casting dies are often far too complex to derive results

6 Zahvala

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only from these engi-neering specifications. The same applies to conformal cooling channels that originate from segmenta-tion strategies or from additive manufacturing. Thus, the complete implementation into the design pro-cess is desirable in order to gain a precise knowledge about the temperature distribution.

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