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Determination of transient heat transfer by cooling channel in high-pressure die casting using inverse method

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Abstract. Complex shapes of aluminum castings are typically manufactured during the short cycle process known as the high-pressure die casting (HPDC). High productivity is ensured by introducing die cooling through a system of channels, die inserts or jet coolers. Die cooling can also effectively help in reducing internal porosity in cast components. Accurate simulations based on sophisticated numerical models require accurate input data such as material properties, initial and boundary conditions. Although the heat is dominantly dissipated through die cooling, indicating the importance of knowing precise thermal boundary conditions, open literature lacks a detailed information about the spatial distribution of heat transfer coefficient. This study presents an inverse method to determine accurate heat transfer coefficients of a die insert based on temperature measurements in multiple points by 0.5 mm K-type thermocouples and a subsequent solution of the two-dimensional inverse heat conduction problem. The solver was built in the open-source CFD code OpenFOAM and the free library for nonlinear optimization NLopt. The results are presented for the commonly used 10 mm die insert with a hemispherical tip and coolant flow rates ranging from 100 l/h to 200 l/h. Heat transfer coefficients reach values well above 50 kW/m^{2}K in the hemispherical tip, which is followed by a secondary peak and then a gradual drop to values around 1 kW/m^{2}K further downstream.

1. Introduction

Complex shapes of aluminum castings are typically manufactured during the high-pressure die casting (HPDC) process. High productivity and internal quality of components is guaranteed by introducing cooling channels or often a system of die inserts pressed into the die. The die insert is water-cooled from inside with the help of a jet cooler and helps to dissipate heat from hardly accessible locations in the casting. With the advent of technological processes such as Gigacasting [1] and the selective laser melting (SLM) ideal for prototyping conformal cooling [2], it is even more necessary to gather accurate thermal boundary conditions (BC) for commercial casting simulations nowadays often assisting in die casting companies [3]. The thermal BC can be also determined using the numerical methods; however, with significant limitations and disadvantages [4]. (I) A casting simulation considering the fluid flow in

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the cooling channels generally results in unacceptably high computational costs. (II) Fluid flow of a single phase will be modelled. Hence, the occurrence of the nucleate or the film boiling cannot be captured. (III) Simulation of the jet impingement phenomenon requires deployment of complex turbulence models, resolution of the viscous sublayer and hence, fine and large meshes [5]. (IV) The shape and the quality of the heat transfer surface of the coolant channel influence to a great extent the convective BC of interest.

The inverse heat conduction problem (IHCP) is an attractive alternative to the fluid flow simulation based on measurements of internal temperatures in the die and a subsequent numerical determination of the unknown BC as it removes the aforementioned drawbacks and it is the central topic of this study [6].

2. Experiment

The layout of the experiment can be seen in figure 1. A die insert with a blind hole, which is ended by a hemispherical tip, is coaxially fitted with a small tube – a jet cooler. A coolant (water) is supplied through this tube. The flow makes a U-turn in the hemispherical tip to leave through the annular section. The hot work tool steel 1.2343 ESR is the material of the die insert. The die insert extracts the largest amount of heat in the hemispherical tip, where the cold jet impinges firstly impinges onto the hot surface. For this reason, a temperature distribution should be primarily known there and hence, more thermocouples (TC) are placed around the hemispherical tip. As seen in figure 1-a, altogether six K-type 0.5 mm grounded TC, referred to as TC_2 – TC_7 consecutively from the top to the bottom, were fitted into six 0.53 mm blind holes drilled into the die insert. Their position was secured by a high-temperature epoxy glue. Normal distance of the TC tips from the heat transfer surface was around 1 mm. One more TC (K-type 1 mm grounded), referred to as TC_1, was attached to the top face of the die insert, further in the text referred to as a contact surface. It was attached in such a way that the TC tip was continuously pushing to the die insert to ensure a stable contact. All TCs were connected to the datalogger Ht800 to record the temperatures at the sampling rate of 80 Hz. Prior to each experiment, the contact surface of the die insert was repolished by hand with a sandpaper 1000 grit.

(a) (b)

Figure 1. Experimental setup with seven thermocouples (red circles) used in the study: (a) a jet cooler in a die insert with a U-turn flow in the hemispherical tip, a molten metal sitting at the top and an insulation material attached to the side; (b) the experimental rig with the inlet/outlet tubes running down from the opened furnace and thermocouples TC_1 – TC_7 connected to dataloggers.

The steps of the experiment are summarized in the following text:

- Water removed from the die insert before the heating step in the furnace,
- Keep the die insert (figure 1-b) in a furnace at 200°C until steady state temperatures reached,

- Melt the aluminum alloy brick ingot (AlSi9Cu3) in a furnace at 750°C for 3 hours,
- Start temperature recording into datalogger Ht800 with the sampling rate of 320Hz,
- Open the door of the furnace and pour the molten metal (0.5 kg, the thickness of 50 mm) into the cylindrical fibrous insulation within less than 5 seconds,
- Hold up for a defined amount of time (120 s or 20 s),
- Start the cooling and wait for another 60 seconds,
- Stop cooling, stop temperature recording, download temperature data and filter the noise.

3. Numerical model

The solver was developed in the open-source CFD code OpenFOAM [7] and the free C library for nonlinear optimization NLopt [8]. The solver is designated for reconstruction of transient two-dimensional BC by solving the inverse heat conduction problem. Here, the solver results from earlier works of the authors in [9,10]. In this study, the transient heat conduction equation is the governing equation to be solved in the space domain Ω enclosed by surfaces Γ, as shown in figure 2-a. If an initial temperature field T_0 and complete BC at Γ were known, a unique solution could be found by solving the so-called direct task. Since information about the BC is incomplete, known only at Γ_{side}, Γ_{top} and Γ_{bottom}, the inverse task must be solved to reconstruct the missing BC at Γ_{HTC}. In order to be able to do so, additional information about the temperature history inside the space domain Ω must be known. Here, the IHCP is formulated using the following governing equation, initial conditions, BC and the least-square problem coupling the BC at Γ_{HTC} and the temperature T_i at time t in the ith internal point of the space domain Ω.

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = 0 \qquad (\in \Omega, t > t_0) \tag{1}$$

$$T = T_0 \qquad (\in \Omega, t = t_0), \tag{2}$$

$$\begin{gathered} -\lambda \nabla_n T = 0 \qquad (\in \Gamma_{side}, t > t_0)\ , \\ -\lambda \nabla_n T = HTC_{top}(\mathrm{TC}_1 - T) \qquad \left(\in \Gamma_{top}, t > t_0\right) \qquad \text{and} \qquad T = \mathrm{TC}_7 \qquad (\in \Gamma_{bottom}, t > t_0) \end{gathered} \tag{3}$$

$$-\lambda \nabla_n T = HTC(T_S - T_\infty) \qquad (\in \Gamma_{HTC}, t > t_0) \tag{4}$$

$$T = \mathrm{TC}_i \qquad \forall i = \{1, \dots, 7\} \qquad (\in \Omega, t > t_0) \tag{5}$$

In equation 1, ρ, c_p and λ stand respectively for temperature dependent density, specific heat and thermal conductivity. The initial condition T_0 depends on the spatial coordinates. Equation 3 denotes a priori known BC, as can be seen in figure 2-a. Equation 4 denotes the unknown BC, in which T_S and T_∞ represent the wall temperature and the reference temperature ($T_\infty = 20°\mathrm{C}$) respectively. The spatially and time dependent HTC is the unknown at Γ_{HTC}. Equation 5 represents TC records from the experiment at different points i in the space domain Ω seeded near the surface Γ_{HTC}. Only the TC_1 is measured at Γ_{top}. Temperature TC_7 is imposed as BC at Γ_{bottom}, but it is also used to determine HTC. To find $HTC \in \Gamma_{HTC}, t > t_0$ the difference between the experimental temperatures $\mathrm{TC}_2 - \mathrm{TC}_7$ and the model temperature T_i at the internal points i must be minimized. The minimization problem can be written as:

$$\forall t \ \text{ find } HTC_t \text{ so that } F = min \sum_{i=2}^{7} (\mathrm{TC}_i - T_i)^2 \tag{6}$$

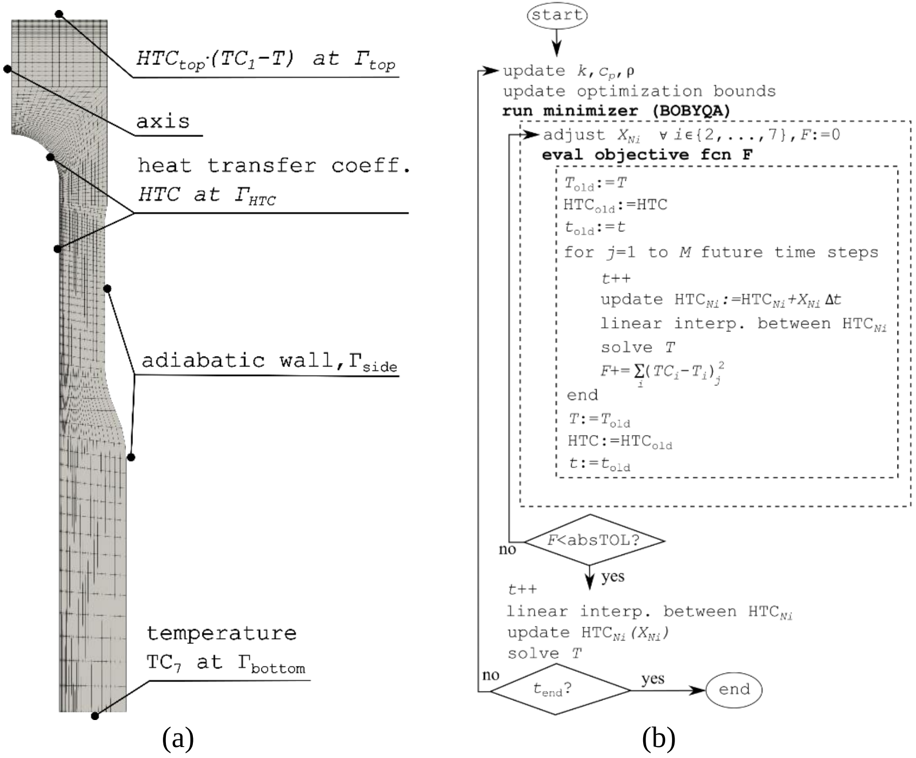
To solve the IHCP a stabilization algorithm is generally required to ensure convergence of solution. This is done by considering the temperature information from the future (equation 5) and the following least-square problem needs to be solved:

$$\forall t \quad \text{find } HTC \text{ so that } F = min \sum_{j}^{M} \sum_{i=2}^{7} (\mathrm{TC}_i - T_i)_j^2, \tag{7}$$

in which the number of future timesteps M was set to 6 in this study. Attention must be also paid to the spatial discretization of HTC on the surface Γ_{HTC}, which appears as a curved surface in figure 2-a. A piece-wise linear interpolation of HTC values is done between two neighboring HTC_N, where N is a point on the surface Γ_{HTC} created by the normal projection of each TC tip onto it. In other words, each TC is linked with exactly one HTC value at the corresponding point N on the surface Γ_{HTC} at the time t. The time discretization of HTC is done assuming the following functional form:

$$HTC_{t+j} = HTC_t + \textstyle\sum_{j=1}^{M} X \cdot \Delta t \qquad \text{with } \ j = 1, \ldots, M, \tag{8}$$

in which Δt is the timestep ($\Delta t = 0.0125\ s$) and X is the rate of change of HTC. It becomes clear that X is the parameter of optimization. In fact, it is a vector with the number of components identical to the number of 0.5 mm TCs, hence, six TCs. The bound optimization by quadratic optimization (BOBYQA) is used to determine the parameter vector X. It was shown in [9] that BOBYQA outperforms other popular minimizers such as Cobyla, Nelder-Mead, Subplex, and BFGS methods. A diagram of the present IHCP solver is shown in figure 2-b. To accelerate convergence of BOBYQA the lower and upper bounds are imposed to the parameter vector X. Furthermore, the absolute tolerance $absTOL$ of the parameter vector X is considered as a stopping criterion and signal to proceed to the next timestep.



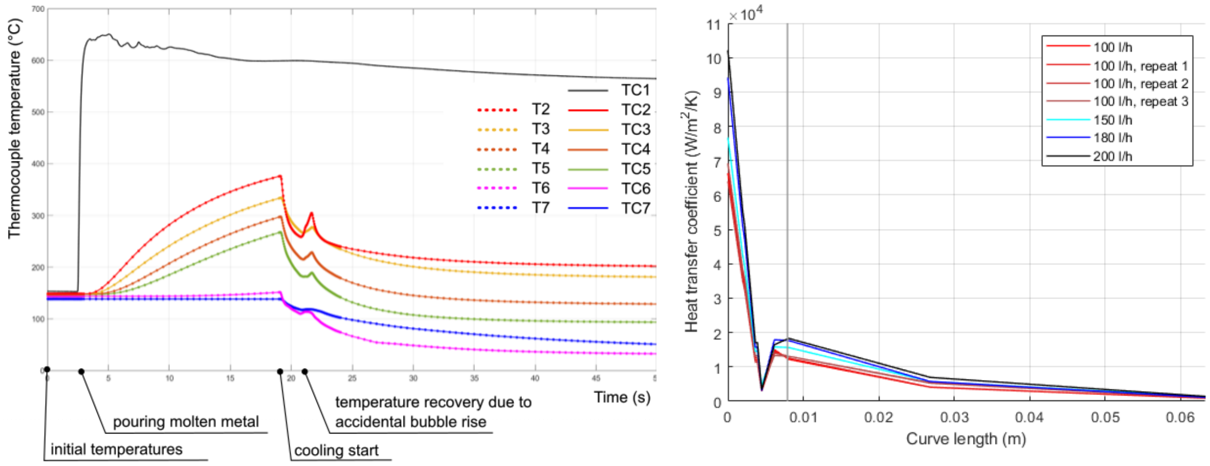
(a) (b)

Figure 2. Prerequisites of the simulations performed in this study: (a) the geometry, the unstructured mesh with 3600 quadrilateral cells and the boundary conditions explained; (b) the sequential algorithm of the two-dimensional inverse heat conduction problem implemented in OpenFOAM using NLopt.

4. Simulation, results and discussion

Recall that simulations were preceded by experiments to obtain the temperature records (equation 5) at locations shown in figure 1-a. These temperature curves can be seen in figure 3-a. In what follows all necessary steps are provided, which eventually results in successful determination of the heat transfer coefficient HTC on the curved surface Γ_{HTC} of the die insert.

- Initialize the non-uniform temperature field using TC1 – TC7, assuming piece-wise linear variation only along the vertical axis of the die insert.
- Run the direct heat conduction simulation in the optimization loop from $t = 0$ s till the start of the cooling (as marked in figure 3) to determine a constant value of HTC_{top} at Γ_{top} (see figure 2-a) for subsequent IHCP calculations of HTC at Γ_{HTC}. During this step, assume $HTC = 0\ \mathrm{Wm^{-2}K^{-1}}$ at Γ_{HTC}. Use $F = min \sum_{j=0}^{coolStart} \sum_{i=2}^{7} (\mathrm{TC}_i - T_i)_j^2$ as the objective function.
- Prior to the IHCP calculations, adjust the position of each TC in the perimeter aligned with TC's silhouette observed in the CT image by minimizing one by one the difference between the measured TC_i and the calculated cooling curves T_i till the start of the cooling. Use $F = min \sum_{j=0}^{coolStart} (\mathrm{TC}_i - T_i)_j^2$ as the objective function with $i = 2, \ldots 7$.
- Run the IHCP solver from the $t = 0$ s till the end of the experimental temperature records to determine HTC at Γ_{HTC}.



(a) (b)

Figure 3. (a) Temperature curves (solid lines) as recorded by the thermocouples TC_1–TC_7 and the temperature curves T_2-T_7 (circle markers) resulting from the solution of the IHCP for the flow rate of 100 l/h; (b) Time-averaged heat transfer coefficient along the surface Γ_{HTC} for flow rates 100 – 200 l/h.

It is evident from figure 3-a that the present IHCP solver ran stably and converged very well to all experimental temperatures. Temperatures of the die insert gradually grow after pouring the molten metal until they abruptly drop when the cooling is started. In figure 3-a, otherwise smooth cooling is disturbed by an accidental pocket of air present in the water supply. In figure 3-b, time-averaged HTC are shown as a function of position on the surface Γ_{HTC}. The arithmetic average was calculated from thousands of values between the start of the cooling (20 s) and the end of the experiment (50 s). At the stagnation point HTC values reach maximum values due to the fact that the cold jet first touches the surface Γ_{HTC}. The thermal boundary layer is not yet developed and the surface temperature is thus close to that of the coolant, which explains high HTC values. As boundary layers develop in the laminar regime further downstream, the coolant temperature as well as the surface temperature rise and the corresponding HTC values drop significantly, which can be seen as the local minimum in figure 3-b. Soon after that, a transition from the laminar to the turbulent regime occurs, which is accompanied by the secondary peak of the HTC values followed by a slow decay of the HTC values along the length of the annular section of the die insert. Figure 3-b clearly reveals a sensitivity, though not dramatic and at some positions only subtle, of the HTC values to the change of the flow rate. When the flow rate is increased, HTC increases also. It is noteworthy that repeating three times the experiment with the flow rate of 100 l/h led to nearly identical HTC curves, as can be also observed in figure 3-b, which confirms repeatability of the experiments.

When the time-averaged HTC values are used in the direct task of the experiment, as shown in figure 4, still a very good agreement with the measured temperature curves is noticeable, though the time dependence as well as the rising pocket of air is neglected. The time-averaged HTC become particularly useful as an input for casting simulations in commercial software such as Magmasoft, ProCAST, etc.

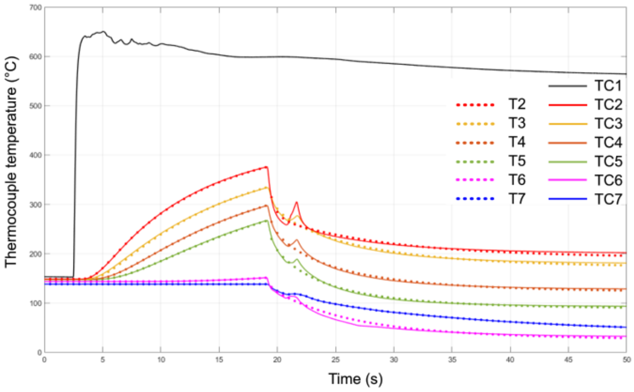


Figure 4. Experimental temperature curves (solid lines) identical to those shown in figure 3-a and the temperature curves (circle markers) calculated in simulation considering the time-averaged HTC from figure 3-b.

5. Conclusions

Cooling intensity of a die insert used in the high-pressure die casting (HPDC) was studied with the help of unique experiments utilizing a molten metal, like in the HPDC, and simultaneous temperature measurements at multiple points inside the die insert using 0.5 mm thermocouples. The experimental data served as an input for subsequent calculations of the inverse heat conduction problem (IHCP). The IHCP solver presented in this study was used to determine transient and spatial variation of the heat transfer coefficient on the curved surface of the die insert. Such information is essential for any follow-up casting simulation conducted in commercial software, which aims at accurate results.

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