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Metal head - dependent HTC in sand casting simulation of aluminium alloys

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Analysis and modelling

ABSTRACT

Purpose: In order to obtain reliable sand casting products, it is essential that the temperature distribution within the alloy during cooling is accurately known at each point by FEM simulation. This requires a great precision in setting the Heat Transfer Coefficients (HTC) at the boundaries. In particular for castings of big size, chills are frequently at different heights, so that remarkable differences arise from the metal head effect.

Design/methodology/approach: An A356 alloy was cast and cooled. The castings were mono-directionally solidified in a experimental equipment modified to accept a controlled variable metal-head. HTC were evaluated in a side arm, where a chill end ensured a dominant unidirectional heat flow during cooling. At the end of a square horizontal channel, an aluminium chill of the same section and 60 mm in depth determined nearly one-dimensional cooling conditions.

Findings: The evolution of heat transfer coefficient (HTC) in the sand casting of A357 aluminum alloy against aluminum chills is evaluated with different metal heads in order to study the effect of pressure on the HTC. Inverse modeling techniques based on Beck's analysis were used to determine the experimental evolution of HTC as a function of time, casting temperature and chill temperature. The HTC evolution at the casting-chill boundary is then described as a function of local parameters such as casting-chill interface pressure (as long as they are in contact) and interface gap (when solidification shrinkage occurs and the casting detaches from the chill).

Practical implications: Finally, the experiments are reconstructed by means of coupled thermal-stress numerical analyses and the predicted cooling curves are fitted to the experimental ones by adjusting model parameters. As a result, the best parameters for describing the HTC evolution are found, thus allowing to extrapolate any possible HTC behavior on chills at different heights for the same casting.

Originality/value: Some transient interface pressure can develop between casting and chill, the effect being negligible in HTC evaluation with the aim to precisely predict the cooling evolution inside the casting.

Keywords: Sand casting; Heat transfer coefficient; Metal head; Stress analysis; Gap formation; A357

1. Introduction

The quality of casting products, so far, has been greatly improved by means of process simulation. In order to obtain effective and reliable results, it is essential that the temperature distribution within the alloy and the mold is accurately known at each point. This requires a great precision in determining the boundary conditions, the most important of which are, in gravity sand casting, the Heat Transfer Coefficients (HTC) between the cast and the chills.

The HTC depend on many factors [1], in relation to the state of the interface. It is generally recognized that alloy temperature [2], formation of a shrinkage gap [3], chill temperature, surface roughness, chill dimension [2, 5], chill material [5] and chill orientation [4], all affect the heat transfer. This, considering the wide range of casting processes and conditions, generally calls for a deeper understanding of HTC modeling in foundry processes.

The importance of the formation of an air gap due to the casting shrinkage is widely known; HTCs are frequently modeled with two distinct formulations, before and after the insurgence of an air gap, respectively. In gravity sand casting, the particular position of the chill surface and the casting contraction behaviour determine different air gaps on different chills.

Before the air gap is formed, the driving parameter for the HTC, beyond the casting temperature, is the interface pressure, which determines the effective contact area between casting and chill and thus the effective area for conduction. In gravity sand casting, the considerable variation in depths (or metal head) of the different chills determine proportional variation of interface pressure, thus determining the spread of cooling conditions at surfaces positioned at different depths.

The effect of metal head height on the casting/mould interfacial heat transfer in gravity casting processes and its correlation with interface pressure has not been thoroughly investigated yet. When a solid shell begins to form in the cast, two distinct phenomena are observed: the casting shrinkage and the chill thermal expansion. Depending on the chill variables (material, dimension, location, surface) and the particular casting shrinkage behaviour, a temporary increase in interface pressure may develop, before the eventual air gap formation. Davies et Al. found a considerable increase in HTC by applying low pressures to the casting surface and tried to explain the experimental behaviour in term of interface phenomena [6-9].

Yet, the considerable difference between foundry practice and experimental setup makes it doubtful to adopt such results to practical cases. Another effect of the metal head on the interface, which to the knowledge of the authors has been never considered, is the delay of the air gap formation; this also determines the increase of the heat flow at different casting depths.

If the effect of pressure on HTC can be recognized, it is not clear how all these effects should be considered in numerical analyses. The aim of this work is to study the effect of the metal head on the interface in sand casting process and to find a proper way of modelling such behaviour in a FEM analysis.

The effect of the metal head on the HTC during solidification of an A357 alloy against aluminium chills is first investigated, by applying inverse modelling techniques [12, 13] on temperature measurements at selected locations in the casting and the chill. The evolution of the HTC is then found as a function of chill temperature and metal head height.

In a second step, the HTC evolution at the casting-chill boundary is considered as a function of local parameters such as casting-chill interface pressure (as long as they are in contact) and interface gap (when solidification shrinkage occurs and the casting detaches from the chill).

The experiments were then reconstructed by means of coupled thermal-stress numerical analyses; there, the numerical parameters of the HTC model were adjusted in order to obtain a best fit between the predicted cooling curves and the experimental ones. As a result, the best parameters for describing the HTC evolution are found, which consider the effect of metal head, thus allowing to extrapolate any possible HTC behaviour on chills at different heights for the same casting.

2. Experimental

An A356 alloy was cast and cooled in an assembly described in [5] and represented in Figure 1. The castings were mono-directionally solidified in a experimental equipment modified to accept a controlled variable metal-head. HTC were evaluated in a side arm (20x20 mm section), where a chill end ensured a dominant unidirectional heat flow during cooling. At the end of a square horizontal channel, an aluminium chill of the same section and 60 mm in depth determined nearly one-dimensional cooling conditions. The surfaces of the chills, made of aluminium, were those typically used in foundry practice, having a square grid 10 mm side of about 1 mm depth grooved on the surface. The particular surface design is aimed at improving the casting-chill contact time. The experiments were specifically developed for replicating typical sand casting manufacturing conditions.

Temperature distributions along the direction of heat flux from the casting to the mould were measured. Two K-type thermocouples of 1 mm diameter were inserted in the chills at 6 and 12 mm from the interface, respectively (Figure 2). Two more thermocouples of 0.5 mm diameter were placed in the casting at 6 and 100 mm from the cooling surface. Three different effective metal heads (150 mm, 300mm and 450 mm respectively) were used by modifying the existing experimental equipment. Temperature data, which were taken every 0.5 second for 200 seconds of cooling, were used for HTC evaluation at the casting-chill interface.

The alloy, melted in an electric furnace, degassed with argon and modified with strontium, was kept still until a temperature of 730 °C was reached; it was then poured into the mold. A silica sand was used in the casting experiments. Before casting, the assembly was heated with a C_2H_2 flame for 10 min from the basin. Each experiment was duplicated for reliability purposes.

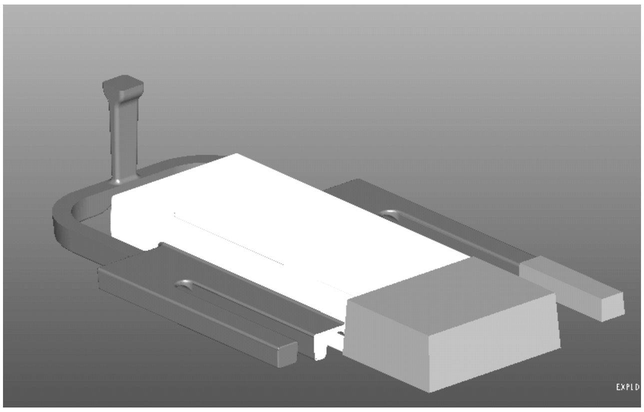

Fig. 1. CAD model of the experimental equipment

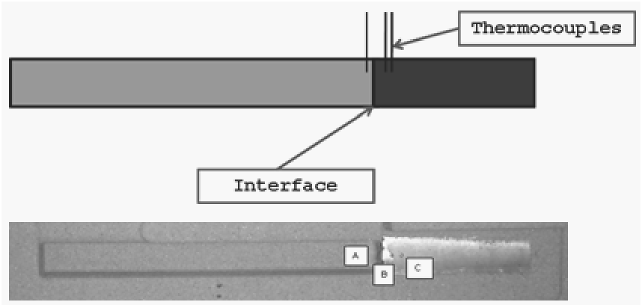

Fig. 2. Thermocouple positioning at the side arm of the casting

3. Inverse analysis and HTC determination

The HTC during solidification were determined using the following procedure (for more details see [5, 9]). An explicit finite difference solution to the one-dimensional inverse heat calculation program [10, 11, 12] was used based on a non-linear estimation method [13]. The procedure takes account of the phase change and temperature-dependent thermal properties of solidification processes. The inertia in the thermocouples during the temperature measurement is also considered.

The two chill temperatures (T2 and T3) are first used to determine the heat flux Q at the chill interface S:

$$Q = -S \cdot \lambda \cdot (T_2 - T_3) \tag{1}$$

where λ is the chill conductivity. Based on the general Fourier Equation for heat transfer, the latent heat of solidification, the surface temperature of the chill Tb_{chill} and the casting temperature $Tb_{casting}$ at the casting-chill boundary can be evaluated. Finally, the chill and casting temperatures at the boundary interface S are used to evaluate the HTC on that surface:

$$HTC(t) = \frac{Q(t)}{S \cdot \left(T_{bcasting}(t) - T_{bchill}(t)\right)} \tag{2}$$

The estimation technique assumes that the heat flux is either a constant or a linear function of time within a given time interval, then determines the heat flux in that period by solving the least-squares problem of the following function:

$$F(q) = \sum_{t}^{N1} \sum_{j}^{N2(N3+1)} (T_{ij} - Y_{ij})^2 \tag{3}$$

where Tij , Yij are the calculated and measured temperatures at location i and time instant j respectively, N1 is the number of internal points in temperature measurement (excluding those used as boundary conditions), N2 is the number of temperature measurements per time interval, N3 is the number of “future” time intervals considered for heat flux calculation in each time interval (the future temperatures at a certain location are the measured temperatures ahead of each time interval, which are used for solving the heat flux or the temperature at the current time interval). By applying $\partial F / \partial q = 0$ for minimization, we have:

$$\sum \sum (Y_{ij} - T_{ij}) \frac{\partial T_{ij}}{\partial q} = 0 \tag{4}$$

Then, using the Taylor series expression of Tij(q), we have:

$$T_{ij}(q_{l+1}) \approx T_{ij}(q_l) + \Theta_{ij} \delta q_{l+1} \tag{5}$$

where $\Theta_{ij} = \partial T_{ij} / \partial q$ can be solved by a numerical method; the following iterative expression for solving the heat flux at each time interval is then obtained [3, 4]:

$$\partial q_{l+1} = \frac{\sum \sum (Y_{ij} - T_{ij}(q_l))\Theta_{ij}}{\sum \sum \Theta_{ij}^2} \tag{6}$$

By repeatedly applying the expression ql+1=ql + δql+1 to correct the heat flux at location q=q0(l=0), the heat flux q at the time interval can be found when δql+1/ql is small enough.

The experimental results are summarized in Figure 3 as a function of casting temperature and of initial metal head. When the cast is between 540°C and 460°C, the HTC evidence a nearly stationary zone where, after reaching a relative minimum, they slightly increase to a secondary peak before the final decreasing phase; this behaviour could be explained by the relative displacements of casting and chill boundaries during this cooling stage, which determines the insurgence of transient interface pressure. In this experiment, higher metal heads push the secondary peaks towards lower temperatures (490-480-460°C in the three cases).

After the secondary peak, the HTC generally decrease and different gradients emerge from one case to another, now with a strong influence of metal head: the greater the metal head, the greater the HTC value. This can be explained by a closer contact of the two surfaces due to the elevated metal pressure in the mushy zone.

4. FEM analysis

The casting processes were reconstructed by numerical analyses. The cooling of the alloy during the filling phase, which was evaluated in a filling analysis of the complete system of Figure 1, was found to be approximately 10°C at the thermocouple location. After this, the numerical model was simplified as represented in Figure 4, with 750000 tetrahedral elements for the cast, 150000 for the chills, 1 mm nodal distance in the whole horizontal arm, chill and casting meshes coincident on the interfaces. Here, only the cooling phase was considered, adopting a starting temperature of 10°C below the experimental inlet temperature.

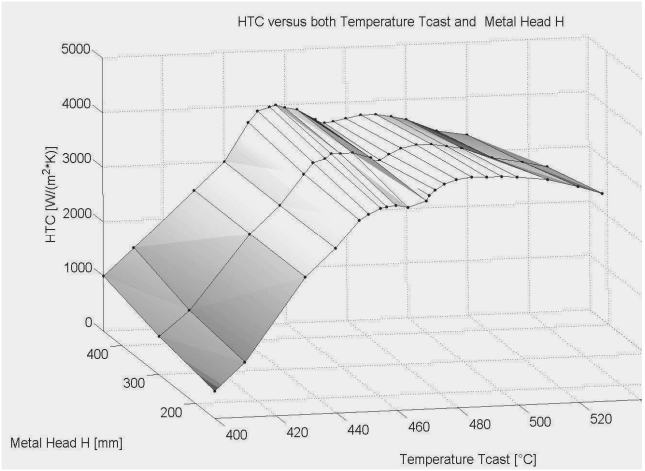

Fig. 3. Evolution of HTC with casting temperature with different metal heads

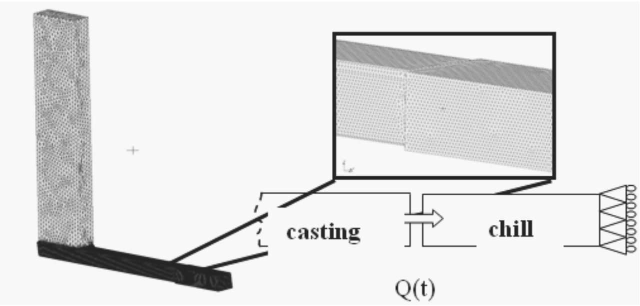

Fig. 4. Geometry of the numerical model

By adopting a thermal + stress solidification analysis, it is possible to correlate the HTC to the interface pressure or the air gap. The adopted models, respectively until the casting and the chill are in contact (Eq. (7)) and when a gap is formed at the interface (Eq. (8)), are the following:

HTC=f(P)
$$HTC = HTC_0\left(1+\frac{P}{A}\right) \tag{7}$$

HTC=f(gap)
$$HTC = \frac{1}{\frac{1}{HTC_0}+\frac{1}{K/gap}} \tag{8}$$

where HTC_0 and A are empirical constants, P the contact force. Concerning Eq. (7), only the parameter HTC_0 could be considered in fitting the experimental values, while A is hard coded in the software. The simulations were run by applying at the top of the inlet section a pressure equal to the metal head of the respective experiments. They were 4000, 8000, and 12000 [Pa] for the 150, 300 and 450 [mm] metal head, respectively. In order to put in evidence the pressure effect, one more simulation was run for each case without applying pressure at the inlet.

The simulations were run with adjusting model parameters until the predicted cooling curves at the interface could fit to the experimental ones (the model parameters remaining the same in the different experiments). As a result, the best parameters for describing the HTC evolution are found, thus allowing to extrapolate any possible HTC behavior on chills at different heights for the same casting.

5. Results and discussion

Figure 5 shows the temperature evolution at the thermocouple location B for the three different metal heads. The three curves are coincident up to 20 s of cooling, when the 150 mm metal head evidences a somewhat slower cooling degree. On the other hand, 300 and 450 mm metal head are practically coincident up to 110 s, when the 300 mm metal head shows a step of temperature increase.

All the curves in Figure 5 show a step of temperature increase when the air gap is formed and the HTC sharply decreases. This, together with the still high temperature gradient within the cast, leads to a temporary increase in temperature at the interface before the heat flow towards the chill can be restored. This phenomenon is clearly confirmed by FEM analysis, as it can be seen in Figure 6a and 6b. There, close agreement is found in the comparison between experimental and simulated temperatures for the 300 and 450 mm metal head; with 300 mm metal head the temperatures are fully coincident until the step of temperature increase, while with 450 mm metal head temperatures coincide up to 50 s of cooling, slightly diverging up to 15° when the air gap is formed at 135-140 [s] of cooling. The onset of the air gap was correctly predicted with 450 mm metal head, while it was postponed by 30-35 s with 300 mm metal head.

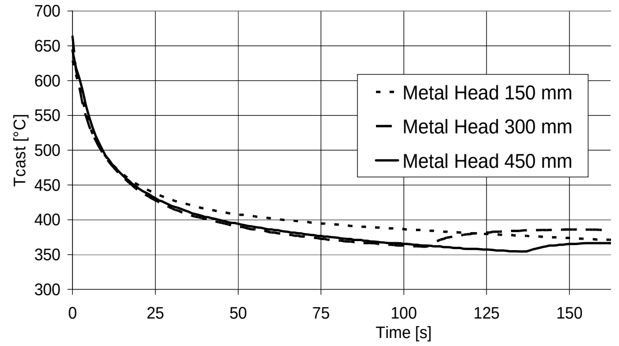

Fig. 5. Experimental cooling curves with different Metal Heads

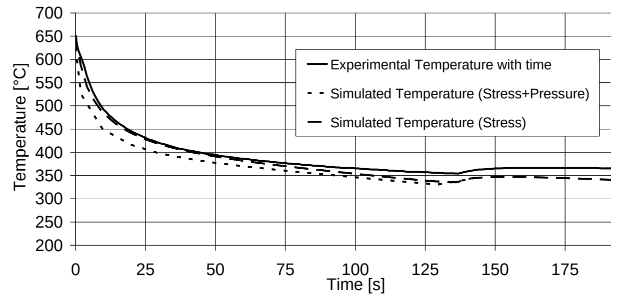

Fig. 6a. Experimental and numerical cooling curves with pressure dependent HTC.Metal Head 450 mm

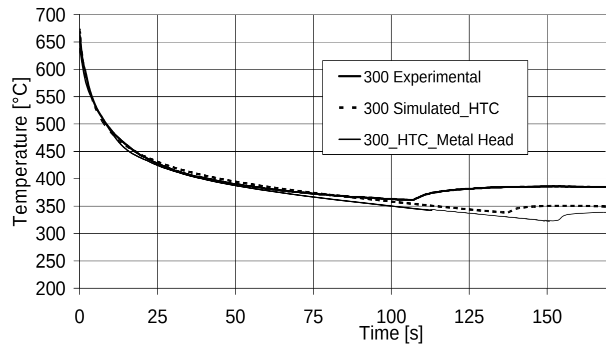

Fig. 6b. Experimental and numerical cooling curves with pressure dependent HTC. Metal Head 300 mm

The close agreement of the experimental and simulated cooling slopes, irrespectively of the formation of the air gap, confirms that the cooling conditions can be predicted with a remarkable confidence by the adopted numerical analysis.

It also emerges, then, that the metal head does not generally affects the heat transfer mode: at least in the first phase of cooling (when solidification structures are formed) the cooling curves are the same. Some difference in cooling behaviour emerges at a later stage: some slower cooling can occur with low metal heads and a delay in the air gap formation can be seen with high metal heads.

In Figure 7 the experimental and numerical HTC are evidenced as a function of time for the 300 mm metal head. The experimental values are reported in [3]. It can be seen how different behaviours emerge at different locations on the interface: in particular, HTC at the centre of the interface are much higher than that at the periphery: the air gap, in fact, develops progressively from the outer points of the interface towards the inside (this fact also confirmed by [4]). Thus, the central points remain in contact up to 120 s cooling, while the periphery detaches already at 30 s. It is also worth noting that the slope of the HTC curves when casting and chill are in contact is almost absent: this means that the effect of pressure is negligible, as it will be discussed later.

It was not possible, here, to define a “global” simulated HTC curve (the HTC is different at each point on the interface): however, this can be considered to be a mixed behaviour between the inner and outer curves depicted, with a global HTC decreasing from 5700 W/m2K at 30 s cooling down to 500 W/m2K at 120 s cooling. This “global” simulated HTC is considerably higher than the experimental one, which decreases from 4000 W/m2K at 10 s cooling down to 500 W/m2K at 100 s cooling. The reason for such difference (remember that simulated and experimental temperatures are coincident throughout the simulation in Figures 5 and 6) lies in the impossibility to evaluate HTC in the first seconds of cooling, when the liquid metals guarantees HTC much above the evaluated ones (see dashed curve in the first 10 s of cooling). Thus, the higher simulated HTC in the 10-100 s time interval would compensate for the lower HTC in the first 10 s of cooling. Nevertheless, this approximation leads to still satisfactory results, as seen.

In Figure 8 the simulated temperature, pressure and HTC at the interface axis with cooling time for the 300 mm metal head at the TA location are shown. Here, it can be noted that the step increase in temperature corresponds with the drop in HTC: moreover, the evaluated interface pressure is evidenced, which was found to be rather constant at 7.5 MPa in the 20-100 s interval, then decreasing to 0 at 120 s. Only after the pressure has become zero, the air gap can form and the HTC sharply decreases.

After the effect of pressure has been explained, it becomes possible to better understand the cooling behaviour for the 150 mm metal head (Figure 5). There, a divergence of HTC from 5700 W/m2K to considerably lower values, before the formation of the air gap (which is somewhat postponed with respect to the other two experiments). In the early stage of cooling, a solid skin forms at the interface which tends to detach from the surface owing to the material shrinkage. The effect of the metal head is, then, to keep in contact the solid shell and the chill interface: if the metal head is too small, the detachment becomes possible, thus leading to a decrease in HTC (as it happened to 150 mm metal head).

Another effect of the metal head can be that of delaying the air gap formation: the 450 mm metal head evidenced an air gap formation about 30 s after that obtained in 300 mm experiment. On the other hand, it was difficult to replicate this behaviour in the numerical simulations: the formation of the air gap were found to be almost insensitive to the metal head pressure applied at the inlet (Figure 6 and 7).

In Figure 9 two different cooling behaviours are evidenced for two different HTC (the first, 5700 W/m2s is the experimental one, the second, 10400 W/m2s can be obtained by applying particular chill materials and cooling methods). It is interesting to note that considerable differences emerge in cooling slopes, in particular in the early stage of cooling. With increasing the HTC the casting cools more rapidly, as expected, and the chill correspondingly more rapidly heats. On the other hand, the lower difference in temperature, between casting and chill, leads to a heat flux not so high as it could be expected. For this reason, although the great difference in HTC, the separation point (when the air gap is formed) is not affected at all, remaining unchanged at 120 s of cooling. Thus, an increase in HTC would lead to more rapid cooling of zones only in proximity of the chill. This is outlined in figure 10, where the cooling rates are evidenced as a function of distance from the chill are evidenced: the increase in HTC leads to a remarkable difference in cooling rate (≥30%) only before 12 mm from the interface, while it has no effect after 20 mm.

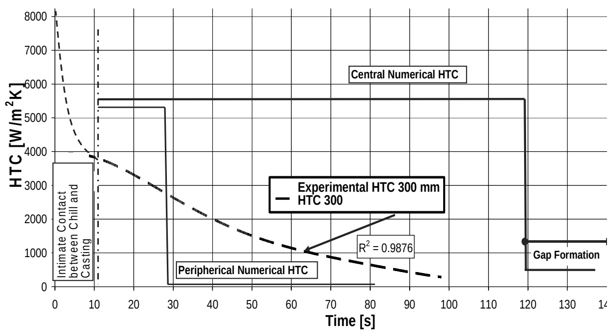

Fig. 7. Experimental and modeled HTC with cooling time (Metal Head 300 mm)

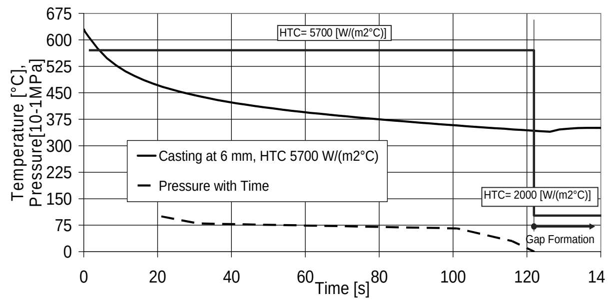

Fig. 8. Simulated temperature, pressure and HTC at the interface axis with cooling time (300 mm metal head, TA location)

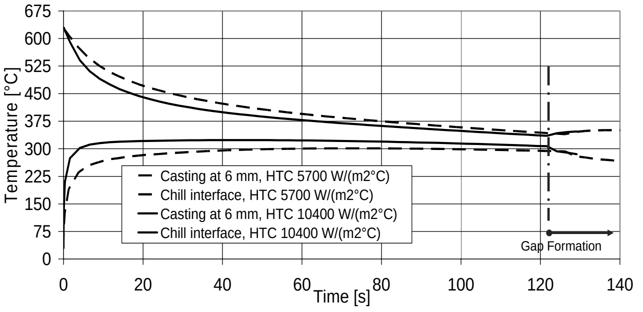

Fig. 9. Simulated temperatures at the interface axis with cooling time (300 mm metal head, TA and TB locations)

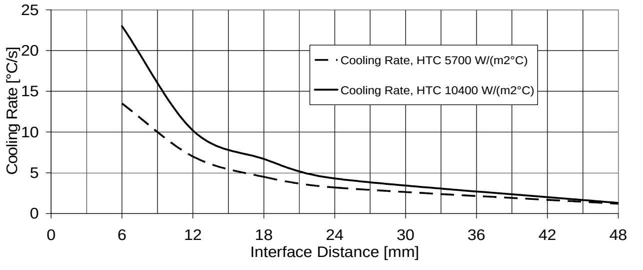

Fig. 10. Simulated temperatures with different HTC with increasing distance from the interface

6. Conclusions

The metal head in gravity sand casting does not affect the HTC in the early stage of cooling, but can lead to significant differences in cooling behaviours if it is too small (HTC can sharply decrease after some solidified skin has formed at the interface) or too large (the formation of the air gap can be delayed).

A fully coupled thermal + stress analysis can effectively predict (with some approximations) the HTC evolution during the whole cooling process and the development of air gaps at the interface. As a result, the casting temperature can be very precisely predicted.

Some transient interface pressure can develop between casting and chill, the effect being negligible in HTC evaluation with the aim to precisely predict the cooling evolution inside the casting.

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