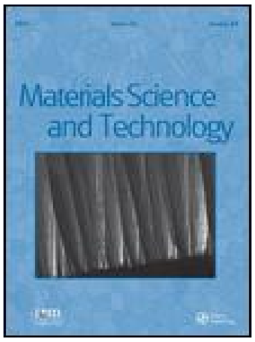

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One-dimensional predictive model for estimation of interfacial heat transfer coefficient during solidification of cast iron in sand mould

K. Narayan Prabhu and W. D. Griffiths

A one-dimensional predictive model is proposed to estimate the interfacial heat transfer coefficients during unidirectional solidification of a cast iron alloy, vertically upwards, against a sand block. The model is based on the surface roughness characteristics of the casting and sand surfaces and the concave deformation of the initial solidified casting skin towards the sand surface. The modelled interfacial heat transfer coefficients and predicted temperatures inside the casting and the sand block showed an approximate agreement with experimentally determined values. The model showed that radiation was a significant mode of casting/sand interfacial heat transfer with the predicted contribution of radiation to the overall heat transfer being nearly 50%. The evaluation of the model in comparison to the interfacial heat transfer models proposed by Zeng and Pehlke suggested that the interfacial conditions considered in this model, namely, the mean peak to valley heights of the casting/sand mould surfaces and the gap width calculated from the deformation of the initial solid skin, gave a more accurate prediction. This predictive heat transfer model has an advantage over the inverse modelling technique as the matching of experimentally measured temperatures to determine the boundary conditions is avoided and the heat transfer coefficients can be estimated as an integral part of the casting simulation. MST/4715

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List of symbols

D	equivalent deformation height
D_p	mean diameter of the sand particles
G	temperature gradient
h	casting/sand interfacial heat transfer coefficient
k	thermal conductivity
R	radius of curvature
R_z	mean peak to valley height within a surface profile
$R_{z(\Sigma)}$	sum surface roughness parameter
T_{casting}	casting surface temperature
T_{sand}	sand surface temperature
α	coefficient of thermal expansion of grey cast iron
Δx	spacing between nodes in the explicit finite difference calculation
ε	emissivity
σ	Stefan – Boltzmann constant

Introduction

The success of solidification simulation in commercial applications to predict the thermal history and the occurrence of casting defects depends largely on the boundary conditions of heat transfer at the interface between the casting and the mould. Currently the solidification modeller has to rely on the literature for heat transfer coefficients that may not exactly represent the casting/mould interface conditions of the process being modelled. For example, the heat transfer coefficient has been shown to be a function of many variables such as time, casting/mould material, mould coatings, surface roughness, casting orientation, etc.[1–4] Alternatively the heat transfer coefficients to be used in the solidification model could be determined experimentally, however this process is time consuming and needs careful and extensive experiments. Although there are empirical models[5,6] available for the prediction of heat transfer coefficients, their use is limited as the results cannot be extrapolated beyond the range of the original experimental data used in building the models. A heat transfer model which takes into account the actual mechanism of heat flow at the casting/mould interface and is capable of predicting the heat transfer coefficient during the solidification of castings would be extremely useful for solidification modelling.

The metal/mould interface is formed by two surfaces and presents a resistance to heat flow during casting solidification. The surface irregularities of the solidifying casting skin result in irregular contacts between the rough mould wall and the casting. Ho and Pehlke[7,8] investigated the mechanism by which heat is transferred at the interface and suggested that during the initial stage a thin skin of the solidified metal formed in contact with the mould or chill surface. This casting skin may physically separate from the mould or the chill when conditions are favourable resulting in an 'air gap'. The mode of heat transfer through this gap has been suggested to be due to both conduction and radiation, with conduction being the predominant mode, especially for relatively low melting point alloys like aluminium and lead.

Many research workers have proposed quantitative models for the heat transfer coefficient based on the formation of an air gap. Nishida *et al.*[9] modelled the formation of the air gap using an analytical elastic model for predicting the movement of the mould wall relative to the casting surface. Huang *et al.*[10] described a free thermal contraction method for modelling the heat transfer coefficient at the casting/mould interface. A finite element model to represent thermal transport phenomena at the casting/mould interface was proposed by Huang *et al.*[11] while Ransing and Lewis[12] have described a thermoelastoplastic model for determining the interfacial gap, and hence the heat transfer coefficient, and applied this to a gravity die cast aluminium alloy casting.

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More detailed representations of the nature of the casting/mould interface include work by Sharma and Krishnan[13] who modelled the heat transfer coefficient associated with the penetration of the liquid alloy into the valleys of the roughness of the surface upon which it rested. Chiesa[14] proposed a heat transfer model through a casting/die wall interface based on the thermal resistances of the die/coating/casting interface. Svensson and Schmidt[15] modelled the contact resistance at the metal/die interface during the early stages of solidification in gravity die casting based on the assumption of thermal expansion of gases trapped inside the coating structure and/or die casting surface irregularities.

Griffiths[16] proposed a model of the interfacial heat transfer coefficient during unidirectional solidification of an aluminium alloy, which was as follows. The surfaces of experimental castings in contact with a chill were found to be convex towards the chill and the convexity of the casting surface was thought to have been caused by the deformation of the solidifying casting skin soon after its formation (as proposed by Niyama and co-workers).[17,18] The heat transfer model included the heat flow through the actual contact area between a plane chill surface and a spherical casting surface and the heat transfer through the voids between. It also took into account the local separation of the casting and the chill surfaces at the circumference of the interface caused by the deformation of the initial solid skin.

The problem of heat transfer between a ferrous alloy and a sand mould is more complex and has been relatively little studied. There is less understanding, and less information to guide the solidification modeller, on heat transfer mechanisms in sand casting than in die casting.

Zeng and Pehlke[19] analysed the heat transfer during solidification of grey cast iron by using two models of the interface at metal/dry sand mould boundaries. The first model assumed no microgap formation at the interface. The second model of the interface described a gap formation with the gas in the gap assumed to be CO_2. The work showed that the heat transfer coefficient for the interface with gap formation could be calculated by consideration of both gas conduction and radiation. The results of their analyses indicated that the fraction of heat transfer by radiation was substantial, around 0·35, and too large to be neglected. The paper also highlighted the lack of a mathematical description of gap formation for sand castings in the literature, which necessitated dependence on experimental measurements of the gap for the determination of the heat transfer coefficient.

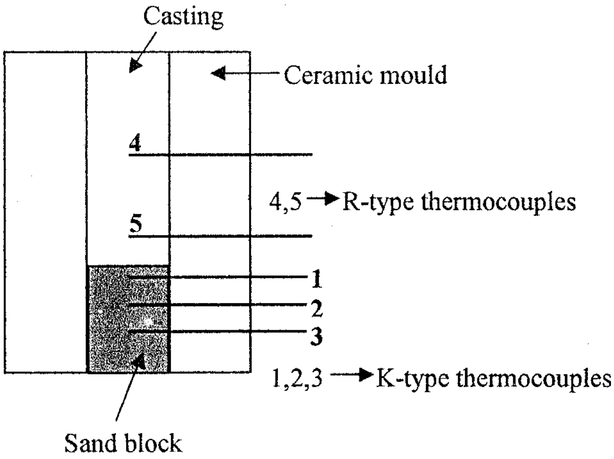
A mathematical model for air gap formation at the metal/green sand mould interface during solidification of Al–12 wt-%Si alloy was proposed by Shahverdi *et al.*[20] This model was based on a combination of the analytical solution of the thermoelasticity equations and a numerical method for heat transfer modelling.

Kubo and Pehlke[21] proposed a model to describe heat and moisture transfer in green sand moulds. However the results from this model were based on a previously determined constant value of the interfacial heat transfer coefficient.

In this paper a model of the heat transfer at the metal/sand mould interface capable of predicting heat transfer coefficients, based on the surface characteristics of the mould and the casting, has been proposed. The predicted values of the heat transfer coefficients and the temperatures in the sand block and the casting were compared with experimentally measured values to validate the model.

Experimental determination of heat transfer coefficient

Cast iron of average composition Fe–3·34C–1·68Si–0·67Mn–0·013P (wt-%) was melted in a high frequency induction furnace. The liquid melt was inoculated using 0·3% ferrosilicon before pouring at a temperature of around 1300°C into low thermal conductivity ceramic moulds, of internal diameter 50 mm and length 50 mm, with a cylindrical sand block, (of green or dry sand, with and without sea coal), of 50 mm diameter and 50 mm length placed at the bottom.



1 Experimental arrangement used for estimation of heat transfer coefficients

The mould/casting experimental arrangement is shown schematically in Fig. 1. Three K type mineral insulated thermocouples (1,2,3) of diameter 1 mm were inserted on the axis of the cylindrical sand block at positions of 2, 10, and 18 mm respectively from the sand block/casting interface, to monitor the cylindrical sand block temperature. In the mould cavity two R type twin bore recrystallised alumina sheathed thermocouples (4 and 5) of 0·45 mm diameter were inserted at the centre of the mould cavity, and 5 mm from the sand block/casting interface, to monitor the solidification process. The thermocouples were connected to a computer controlled data logger and their temperatures recorded at intervals of 0·5 s.

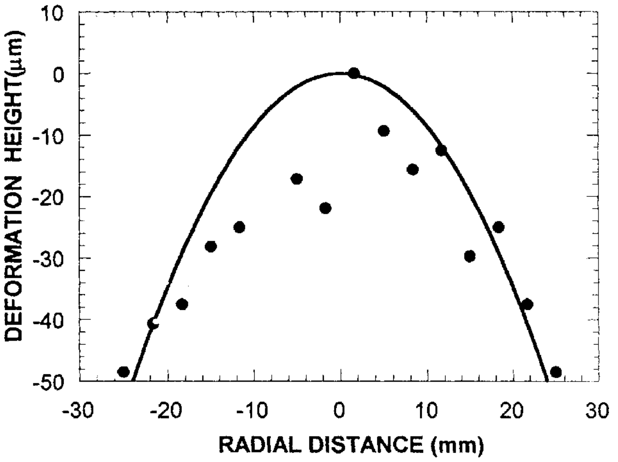
The heat transfer coefficients were estimated from the temperature data acquired from the thermocouples by inversely solving the one-dimensional (1D) transient heat conduction equation. Further details of this technique are given in Ref. 22.

The surface finish parameters of the chill and casting surfaces were measured using an RS Surtronic 200 surface profileometer. The mean peak to valley height of the surface roughness measured in the traverse R_z, was found to be 120 and 150 μm respectively for the cast iron and sand mould surfaces. In addition to surface roughness data, profiles were measured across the diameter of the casting which showed that the casting surfaces were not plane but concave toward the sand surface, indicating that a close contact between the casting and sand surfaces would only occur at the circumference of their interface.

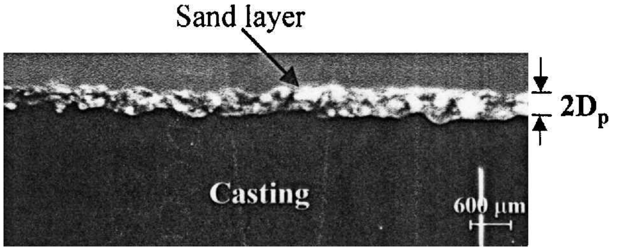
Model of heat transfer through casting/sand interface

MODELLING OF INTERFACIAL HEAT TRANSFER ABOVE SOLIDUS TEMPERATURE

It was assumed that, upon casting of the liquid alloy, the liquid metal rested upon the sand surface and a solid skin formed immediately. This casting skin was assumed to have a negligible thickness, but to have a surface roughness as measured after the casting experiment. The initial temperature of the liquid alloy was assumed to be 1290°C, determined from the casting experiments, and the initial



2 Photograph of sand layer adhering to casting surface



3 Example of surface profile of casting surface in contact with sand block showing concave deformation relative to sand surface

sand temperature was assumed to be 20°C. Heat transfer by conduction between the contact areas of the sand surface and the solidifying alloy was neglected during this stage owing to the small area of contact to be expected and the low thermal conductivity of the sand. Heat transfer was therefore assumed to be due to both conduction and radiation from the thin solid casting skin to the sand surface through the interfacial atmosphere, assumed to be a mixture of 50 mol.-%CO_2, 30 mol.-%CO, and 20 mol.-% water vapour. To determine the mean separation of the casting and chill surfaces, the surface roughness of both were combined into a sum surface roughness as follows

$$R_{z(\Sigma)} = (R^2_{z(\mathrm{sand})} + R^2_{z(\mathrm{casting})})^{1/2} \quad . \ . \ . \ . \ . \ . \ . \ . \quad (1)$$

(This results from the assumption that two rough surfaces in contact may be approximated by a sum rough surface in contact with a plane surface, where the surface roughness parameters are treated as in equation (1).)[23]

The heat transfer coefficient for the initial contact stage h_i was therefore determined from the sum of the heat transfer by conduction and by radiation using

$$h_i = h_c + h_r \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (2)$$

Here h_i is the total heat transfer coefficient, h_r is the heat transfer coefficient owing to radiation, and h_c is the heat transfer by conduction, (through the atmosphere between the casting and mould surfaces).

The heat transfer owing to conduction is given by

$$h_c = k_g / X \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (3)$$

where k_g is the thermal conductivity of the atmosphere in the interface between the casting and the mould and X is the mean distance between the casting and sand surfaces given by

$$X = R_{z(\Sigma)}/2 \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (4)$$

The radiation heat transfer coefficient is given by

$$h_r = \frac{\sigma(T_{\mathrm{casting}} + T_{\mathrm{sand}})(T^2_{\mathrm{casting}} + T^2_{\mathrm{sand}})}{\varepsilon^{-1}_{\mathrm{casting}} + \varepsilon^{-1}_{\mathrm{sand}} - 1} \quad . \ . \ . \ . \ . \quad (5)$$

where σ and ε are the Stefan–Boltzmann constant and emissivities of the surfaces respectively.

The casting and sand surface temperatures for the calculation of the radiative heat transfer were estimated by numerically solving the 1D heat conduction equation for the casting and the sand by the explicit finite difference method. The thermophysical properties of the cast iron and the sand were obtained from Refs. 24 and 25 while the thermophysical properties of the alloy were measured.[26] The heat transfer coefficients computed were used in the finite difference simulation until the casting surface node reached the solidus temperature 1120°C. Any possible expansion and contraction associated with the sand chill and the casting was calculated from the coefficients of linear expansion of grey cast iron and silica sand but the relative expansion/contraction of the sand and the solidified part of the casting was found to be negligible and any associated effects were not considered in the model.

HEAT TRANSFER AFTER MOMENT OF DEFORMATION OF INITIAL SOLID SKIN

A layer of sand was observed to adhere firmly on to the casting surfaces, (for example, it could not be removed by ultrasonic cleaning), as shown in Fig. 2. This layer was caused by the penetration of the liquid cast iron into the sand, which might have been due to the metallostatic pressure of the liquid iron, or to the expansion of the sand surface, or both.[27] The thickness of this sand layer was measured using image analysis and the mean value was found to be 380 µm, approximately equal to twice the mean diameter D_p of the sand particles.

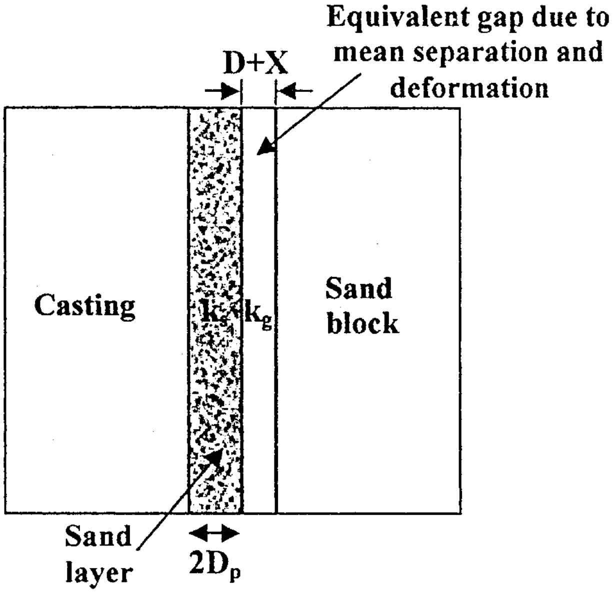
In the model, it was assumed that the casting skin underwent deformation and the shape of the casting surface became concave with respect to the sand block. This concave shape was confirmed by the measured surface profile of the casting surfaces shown in Fig. 3. The heat transfer from the casting to the sand block was now assumed to take place through the sand layer and the gap, determined on the basis of the deformation of the casting skin.

Niyama and co-workers[17,18] using a droplet method, have studied the deformation of the initial solid skin in detail. The direction of the deformation was either positive (convex) or negative (concave) depending upon the composition of the alloy. This deformation occurred almost instantaneously upon contact of the liquid metal with a cold surface, and once the solidified skin had reached a critical thickness. The deformation model developed by them was incorporated in this work. Deformation was assumed to take place once the surface node of the finite difference model of the temperature distribution in the casting reached the solidus temperature of the alloy, (1120°C), with any possibility of undercooling below this temperature neglected. The temperature gradient at the time of deformation was calculated from

$$G = (T_{\mathrm{subs}} - T_s)/\Delta x \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (6)$$

where T_{subs} is the temperature of the subsurface node of the casting, T_s is the temperature of the surface node of the casting, and Δx is the spacing between nodes in the finite difference calculation. In the original model of Dong *et al.*,[18] it was proposed that there was a critical skin thickness at which deformation of the skin occurred, but this had a negligible effect on the results from the model and was not included.

Following the model in Ref. 18, the radius of curvature of the casting surface after deformation was then calculated



4 Schematic representation of overall thermal resistance to conduction of heat from casting to sand block: k_s thermal conductivity of sand layer; k_g thermal conductivity of equivalent gap

from

$$R=(\alpha G)^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where α is the coefficient of linear expansion of grey cast iron. The displacement of the casting surface owing to the deformation y at any point on the radius of the interface r was then determined from

$$y=r^2/2R \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

For example, the predicted deformation at the centre of the casting surface was 51 μm. This was only 11% greater than the measured deformation of the casting surfaces at the corresponding point, which had a mean value of 46 μm.

The deformation height across the radius of the casting surface was calculated and a mean height estimated to represent an equivalent deformation height D along the casting/sand chill interface. The heat transfer by conduction through the atmosphere between the casting and mould surfaces is in series with the heat transfer through the sand layer adhered to the casting surface. Expanding this to include the deformation of the initial solidified skin of the casting results in

$$h_c^{-1}=\left(\frac{k_g}{D+X}\right)^{-1}+\left(\frac{k_g}{2D_p}\right)^{-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

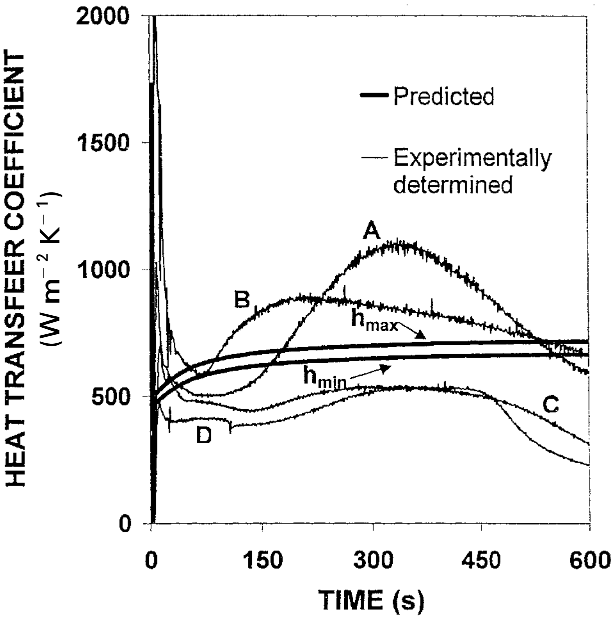
Rearranging equation (9), the heat transfer coefficient owing to conduction is calculated as

$$h_c=\frac{k_g k_s}{k_s(D+X)+2k_g D_p} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where D represents an additional gap and hence an additional resistance to heat transfer occurring owing to the deformation of the casting surface and k_s is the estimated thermal conductivity of the penetrated sand layer. A schematic representation of the overall thermal resistance to heat transfer by conduction from the casting to the sand block is shown in Fig. 4.

The overall heat transfer coefficient was then calculated using equation (2). Expanding this

$$h=\frac{k_g k_s}{k_s(D+X)+2k_g D_p}+\frac{\sigma(T_{\mathrm{casting}}+T_{\mathrm{sand}})(T_{\mathrm{casting}}^2+T_{\mathrm{sand}}^2)}{\varepsilon_{\mathrm{casting}}^{-1}+\varepsilon_{\mathrm{sand}}^{-1}-1} \quad . \quad . \quad . \quad . \quad (11)$$



A green sand without sea coal; B green sand with sea coal; C dry sand without sea coal; D dry sand with sea coal

5 Comparison of experimentally determined and predicted heat transfer coefficients h_{max} and h_{min}

The model of heat transfer given by equation (11) was used to calculate the heat transfer coefficient for a maximum separation at the casting/sand interface. However the experimental measurements showed that the maximum deformation height was almost one third of the mean peak to valley height R_z of the casting and sand surfaces. This would mean that how the two (rough) sand and casting surfaces were in contact at their circumference would determine their actual separation at the interface. The heat transfer would be increased if there was no deformation and the resistance to heat flow was offered by only the sand layer and the mean separation at the interface represented by the sum surface roughness parameter $R_{z(\Sigma)}$. The heat transfer coefficient would then be given by

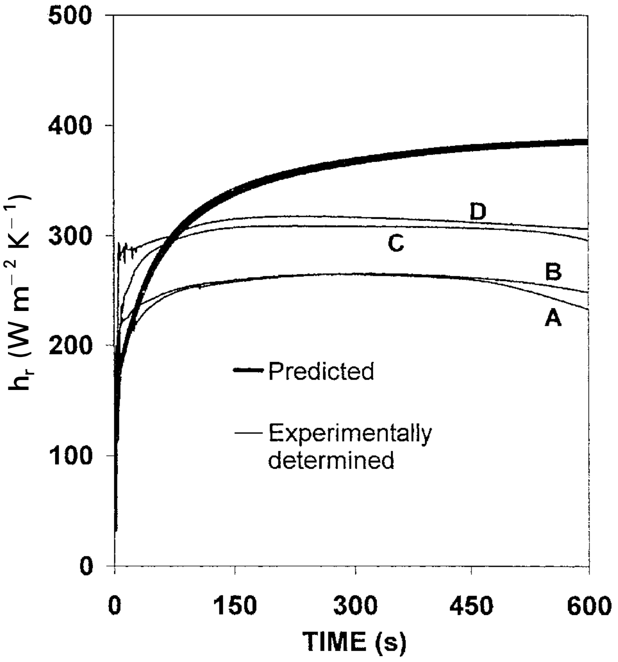
$$h=\frac{k_g k_s}{k_s X+2k_g D_p}+\frac{\sigma(T_{\mathrm{casting}}+T_{\mathrm{sand}})(T_{\mathrm{casting}}^2+T_{\mathrm{sand}}^2)}{\varepsilon_{\mathrm{casting}}^{-1}+\varepsilon_{\mathrm{sand}}^{-1}-1} \quad (12)$$

The model of heat transfer given by equation (12) therefore estimates a maximum heat transfer coefficient for the case of minimum separation at the casting/sand interface.

The heat transfer model was tested for grid size dependency by changing the value of the grid size used in the present investigation (0·5 cm). The values of the heat transfer coefficients obtained showed that the model was independent of grid size, for example, with grid sizes of 1, 0·5, and 0·25 cm, typical values of the heat transfer coefficient obtained were 690, 730, and 739 W m^{-2} K^{-1} respectively.

Results

Figure 5 compares experimentally determined overall heat transfer coefficients obtained during solidification of the cast iron, to the heat transfer coefficients predicted for all types of sand formulations. A comparison of modelled radiation heat transfer coefficients with the experimentally determined radiation heat transfer coefficients is shown in Fig. 6. The experimentally determined radiation heat transfer coefficients were estimated from the casting and sand surface temperatures as calculated by the 1D inverse



A green sand without sea coal; B green sand with sea coal; C dry sand without sea coal; D dry sand with sea coal

6 Comparison of experimentally determined and predicted radiation heat transfer coefficient h_r

heat conduction model. This procedure involved the estimation of boundary surface temperatures from the measured thermal history inside the sand block and the casting.

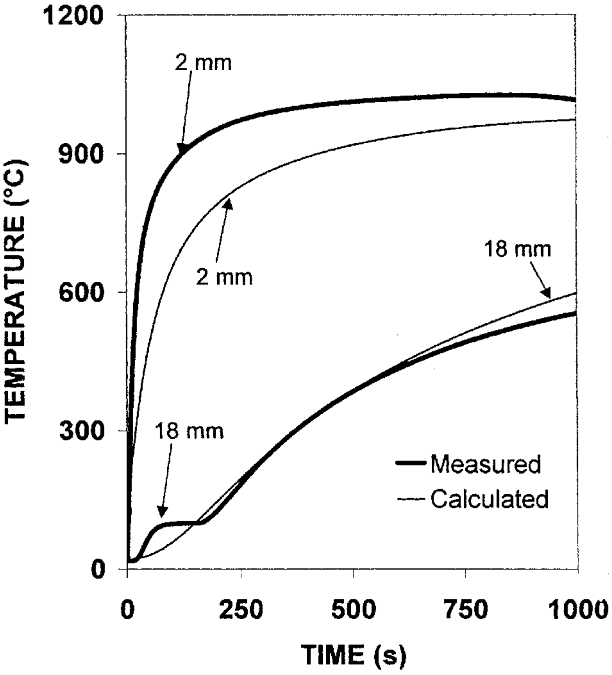
Figure 5 shows the maximum and minimum predicted heat transfer coefficients of the heat transfer model corresponding to minimum and maximum separation at the casting/sand interface. The predicted heat transfer coefficients were within the range of values that were measured experimentally. In fact the experimentally measured heat transfer coefficients in Fig. 5 relate to experiments carried out with both green and dry sand, with and without added sea coal. In the several experiments carried out no discernible difference in the heat transfer coefficients for the different sands was found therefore the model would appear to represent the general case for interfacial heat transfer for cast iron in sand moulds. The predicted radiation heat transfer coefficients (Fig. 6) clearly showed that the contribution of radiation to the overall heat transfer was nearly 50% and constituted a significant mode of casting/sand interfacial heat transfer.

Figure 7 shows a comparison between the temperatures measured in the sand block, 2 and 18 mm from the interface with the casting, with the temperatures at the same point calculated by the model. The calculated temperature at 18 mm shows a close agreement with the measured temperatures. However the calculated temperature at 2 mm from the interface was lower than the measured temperatures by as much as 100°C in the early stages of the experiment. Figure 8 shows a similar comparison between the calculated casting temperatures at 5 and 25 mm from the interface with the corresponding experimentally measured temperatures.

The first stage of the model lasted for only 2 s. The second stage of the model was run for 550 s, by which time the centre of the casting had solidified completely.

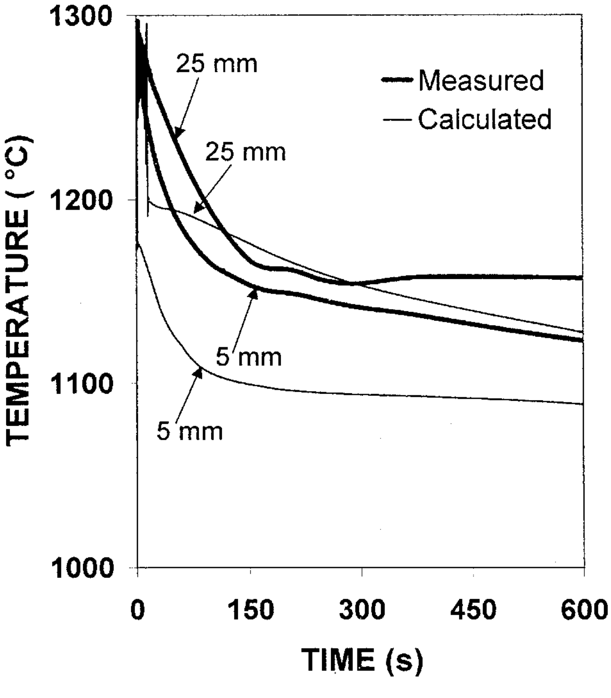
Discussion

The approximate agreement between the measured and predicted heat transfer coefficients, shown in Figs. 5 and 6, and between the calculated and measured temperatures in the sand block and the casting, (Figs. 7 and 8) suggests that the important features that influenced the interfacial heat transfer between the unidirectionally solidified cast iron and the sand block have been recognised. These are radiation and conduction through the interfacial gas.

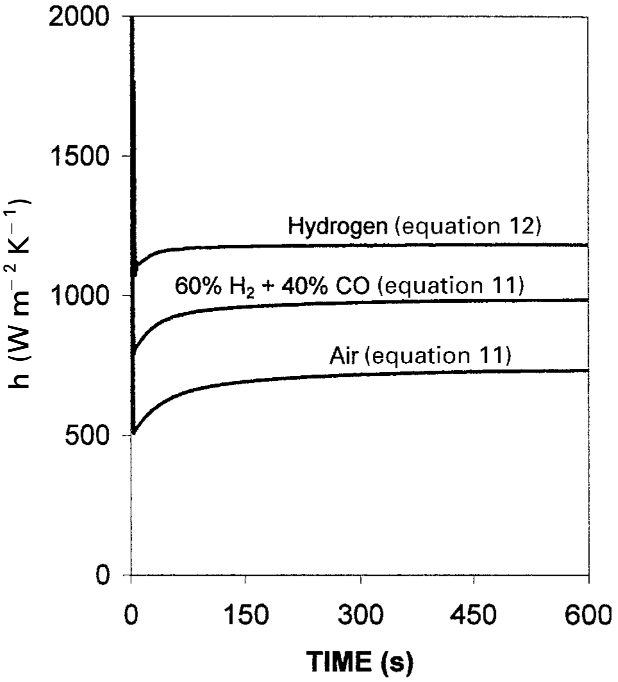


7 Comparison of experimentally measured and predicted temperatures inside sand block

The contribution of radiation estimated by the present model depended largely on the emissivities of the casting and sand surfaces. The casting surface emissivity was assumed to be 0·8 and the sand surface emissivity was measured.[22] However the limited data obtained for the sand surface emissivity showed that it was dependent on temperature and wavelength and this was difficult to adequately represent in the model.



8 Comparison of experimentally measured and predicted temperatures inside casting



9 Estimated heat transfer coefficient *h* when air and hydrogen constitute composition of interfacial gas

The composition of the interfacial atmosphere was assumed and the presence of other gases may alter the predicted heat transfer coefficients. For example, the presence of hydrogen would significantly increase the heat transfer coefficient owing to its higher thermal conductivity. A recent study by Lane *et al.*[28] has shown the composition of the interfacial gas is likely to be 60 mol.-% hydrogen and 40 mol.-%CO during casting of steel. Figure 9 shows the heat transfer coefficients predicted by the model when the atmosphere in the interface was considered to be 100% hydrogen, 100% air and for the interfacial gas composition suggested by Lane *et al.* The values in the first two cases therefore represent the maximum and minimum predicted heat transfer coefficients that could be expected during solidification of cast iron against sand.

Other important features of the model include the consideration of the effect of a deformation of the initial casting skin, evaluated by the estimation of heat transfer coefficients for maximum and minimum separations of the casting and sand surfaces, and also the role of surface roughness, and the inclusion of the effect of an adhered sand layer owing to metal penetration into the sand.

Two possible influences on the interfacial heat transfer were neglected in the model. First, the experiments originally carried out to measure the interfacial heat transfer coefficient[22] showed no evidence of the occurrence of an air gap, (defined as a complete separation of the casting and the sand surfaces). Second, the rate of relative expansion and contraction of the sand and the casting was evaluated in the model and found to be negligible, (although it is acknowledged that this is an important effect that could markedly influence interfacial heat transfer in a real sand mould, by altering the amount of contact at the interface).

An additional consideration is that thermal distortion of the casting during cooling, and of the sand block during heating, (caused by the generation of thermal stress by the temperature gradients within each), was not considered in the modelling of the heat transfer coefficients.

The agreement between the experimentally measured and predicted temperatures was reasonably good at locations away from the interface. However there was clearly a divergence at locations close to the interface. This may be caused by the deformation of the initial solidified casting skin, resulting in the separation of the curved casting surface from the sand surface, which would be at its greatest at the central region of the interface. (The thermocouples from which the heat transfer coefficients were determined were placed on the centreline of the casting sand block arrangement.) Therefore a precise agreement cannot be expected between experimental result and the model of the boundary conditions, (the interfacial heat transfer coefficient and the subsurface temperatures), since true 1D heat transfer did not occur close to the interface.

The model was constructed for a unidirectionally solidified casting. However, during the actual experiment 1D heat transfer cannot be solely the case. The refractory walls of the mould conduct some heat and this may have affected the thermal history measured inside the casting and the sand block. However, the heat transfer coefficient at the metal/ceramic mould interface, calculated from the rise in temperature of the refractory block, was estimated to be only around 45 W m^{-2} K^{-1}. This was ~8% of the measured interfacial heat transfer coefficient between the casting and the sand block. Furthermore, thermocouples located at the same depth inside the sand block, but at different radii, recorded slight differences in temperatures. This showed that the heat flow through the sand blocks was not truly 1D.

Nonetheless the present model overcomes some of the limitations of the interfacial heat transfer model proposed by Zeng and Pehlke.[19] For example, in the Zeng and Pehlke model, the interface between the casting and the sand mould was treated as a case of imperfect contact throughout the period of solidification and the possibility of the deformation of the initial solidified casting skin was not considered. Further, the heat transfer coefficients predicted by their model, which varied from 30 to 45 kW m^{-2} K^{-1}, seem to be extremely high for sand moulds. The second model proposed by them used experimentally measured values of the casting surface and mould wall movements for the determination of an interfacial gap width and hence a heat transfer coefficient. These values were significantly lower (250 – 2000 W m^{-2} K^{-1}) than the heat transfer coefficients predicted by the first type of model and much more realistic.

The predictive model presented in this paper did not involve experimental measurements to calculate the heat transfer coefficient. The model uses the mean peak to valley heights of the mould and casting surfaces to assess the initial imperfect contact condition and the gap width was calculated using a model of the free deformation of the solidified casting skin. Figure 10 shows a comparison of heat transfer coefficients calculated using the gas gap model of Zeng and Pehlke[19] with the values estimated using the proposed model.

Conclusions

A heat transfer model has been presented to predict the interfacial heat transfer coefficient during unidirectional solidification, vertically upward, of a cast iron alloy against a sand block. A good agreement between the experimentally determined heat transfer coefficients and the modelled heat transfer coefficients was obtained and indicated that radiation and conduction through the interfacial atmosphere were the significant modes of heat transfer at the casting/sand interface.

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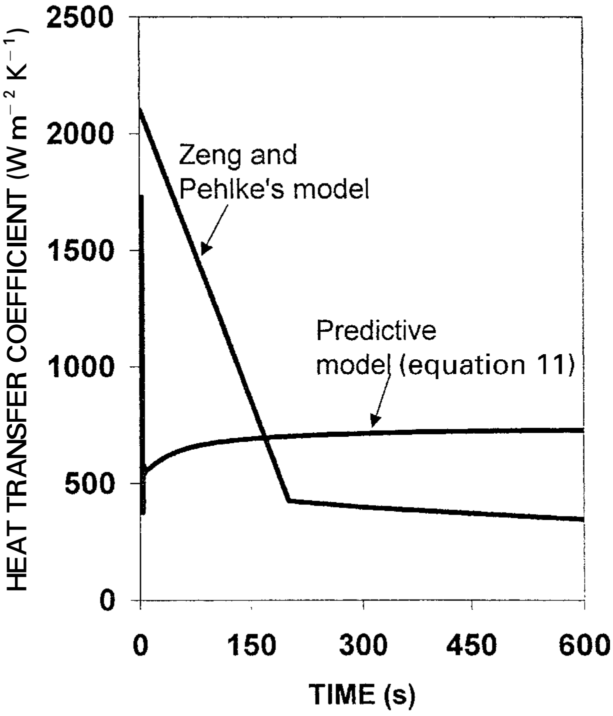

10 Comparison of heat transfer coefficients from gas gap model of Zeng and Pehlke[19] with values predicted using proposed model

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