A New Approach for Modelling Slag Infiltration and Solidification in a Continuous Casting Mould

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A mathematical model of the continuous casting process has been developed which couples metal, slag and gas flow with heat flux and solidification. An extensive sensitivity study has been carried out with this model, studying the influence of changing casting conditions upon a number of quantifiable model predictions (i.e. responses). The casting conditions studied were: casting speed, mould flux properties (viscosity, break temperature), mould oscillation frequency and stroke, and superheat. The model was then applied to determine the influence of each of these parameters on the variations in: powder consumption (lubrication), heat flux (solidification) and oscillation mark formation (defects). It is shown that all three responses vary in a consistent manner through the cycle. Equations are derived for the powder consumption and heat flux, showing good agreement with prior experimental data.

KEY WORDS: continuous casting; slag infiltration; modelling; slab casting; solidification; oscillation marks.

1. Introduction

Continuous casting is a highly efficient process with more than 1 billion tonnes of steel cast per year. However, a major hindrance to improve productivity is the formation of defects (e.g. longitudinal and transverse cracking, deep oscillation marks, etc.), which inevitably leads to remedial treatment, disruption to production and down-grading of the final product.

The caster layout, mould and phases present at the meniscus during the continuous casting process are shown in Fig. 1. Steel is poured from the ladle to a tundish and subsequently into a water-cooled copper mould through a submerged entry nozzle (SEN). A steel shell forms against the mould which is pulled downwards through the mould bottom and exposed to water-sprays until solidification is complete. The sticking of the steel shell to the copper mould is prevented by the use of a mould flux and mould oscillation. The mould flux is added continuously to the top of the mould; where it sinters to form a bed and later melts to form a slag pool. Finally, the liquid–slag from the pool infiltrates the gap between the mould and the shell to form solid and liquid films. The thicknesses of the liquid \(d_{\text{liquid}}\) and solid \(d_{\text{solid}}\) slag films control the lubrication and heat flux, respectively; whereas the powder consumption \(Q_s\) (in kg/m\(^2\)) is a good measure of the lubrication supplied, \(Q_s = \rho \cdot d_{\text{liquid}} = 2250 \cdot d_{\text{liquid}}\), where \(\rho\) is the density of the slag.

The development of these slag layers and performance of the continuous caster are dependent upon a number of variables (e.g. casting speed, \(v_c\), oscillation characteristics and mould flux properties). Further, each of these casting parameters can interact with each other. Consequently, when remedial action is taken to minimize one type of defect it may result in the occurrence of another, or cause operational problems. A reliable mathematical model is needed to take these interactions into account and provide predictions of defect occurrence. Nevertheless, the majority of

![Fig. 1. Caster layout, mould and phases present in meniscus.](image-url)
numerical models to date\textsuperscript{1–4} have used certain assumptions (e.g. predefining the thicknesses of the slag films or the meniscus shape), which limit their accuracy when predicting powder consumption and defect formation. Furthermore, although there is general agreement about the effect of casting speed and viscosity on powder consumption, there is considerable uncertainty regarding the effects of oscillation characteristics on this parameter.

Another consequence of mould oscillation is the formation of oscillation marks (OM’s), which are regular, transverse indentations on the surface of the cast products. Oscillation marks themselves are not much of a threat, but these depressions are sites prone to segregation and transverse cracks\textsuperscript{5} and regarded for this reason, as defects.

A mathematical model which couples metal, slag and gas flow to the heat flux is presented in this work.\textsuperscript{6,7} This model makes no assumptions concerning the formation of slag films or meniscus shape in an effort to provide a more fundamental understanding of the phenomena occurring in the meniscus. Mould oscillation was also added to this model as a sinusoidal curve. Typically, this mould oscillation is presented in terms of the ‘negative strip time’ (\(t_n\)) which is the time when the mould is descending faster than the shell (\(v_m > v_s\)) and ‘positive strip time’ (\(t_p = t_{cycle} - t_n\)).\textsuperscript{4,8} In this way, the negative strip time is given by:

\[
t_n = \left(\frac{60}{\pi \cdot f}\right) \arccos\left(\frac{v_s}{\pi \cdot s \cdot f}\right) \quad (1)
\]

where \((t_n)\) is the negative strip time and \((s)\) and \((f)\) are the stroke and frequency, respectively.\textsuperscript{9}

The objectives of this study were to:

- Gain further insights into variations into the powder consumption \((Q_s)\), heat extraction \((q)\) and the oscillation mark depth \((d_{OM})\) through the oscillation cycle.
- Identify the key factors influencing the parameters \(Q_s, q\) and \(d_{OM}\).
- Establish equations to express these parameters as a function of the casting conditions (e.g. viscosity, casting speed, etc.).

In a previous paper\textsuperscript{10} the predictions of this model were used to gain insight into variations of both powder consumption and heat flux through the oscillation cycle. However, the technique was only applied to study casting speed effects. In the present study a larger number of runs have been performed to determine the effects of a variety of parameters (e.g. viscosity, stroke, frequency, etc.) on powder consumption, heat flux and depth of the oscillation marks.

2. Model Description

The model developed in this study couples a flow model with a heat transfer and solidification model. Full details of the numerical method have been published elsewhere.\textsuperscript{10} The flow model is based on ANSYS-FLUENT\textsuperscript{TM} 6.3.26 and solves the Navier–Stokes equations for the metal–slag flow coupled to the Volume of Fluid (VOF) method to calculate the phase fractions of metal and slag.\textsuperscript{10} The metal/slag interface is tracked through the Continuum Surface Force (CSF) method.\textsuperscript{11} The heat flux model solves the Fourier equation, while the heat extracted by the cooling water jacket is calculated using a heat transfer coefficient related to the Nusselt number. The \(k–e\) turbulence model\textsuperscript{12} is used to take into account the turbulence in the system. The heat removal by the mould is calculated through the predicted liquid and solid slag layers after infiltration. The total thickness of the slag film \((d_{slag} = d_{liquid} + d_{solid})\) is divided by its thermal conductivity \(k\) (which varies as a function of the temperature in the gap) and the interfacial resistance \((r_{int})\) at the Cu/slag interface (specified as a function of the CaO/SiO ratio). It should be noted that the model makes no assumptions concerning neither the solid and liquid film thicknesses nor the shape of the steel–slag meniscus. These are both direct predictions by the model.

The 2D domain consists of half SEN, slab mould (width = 1.88 m), water cooling channels and 1 m of slag length after the mould exit. The solid shell surface was located using the phase fraction map, while the interface between solid and liquid slag films was defined by the break temperature \((T_{br})\) of the mould flux. The solution procedure consists of allowing the iso-thermal metal flow to develop for at least 1000 s, then adding the slag bed \((via a 50 mm patch)\) and solving heat transfer for at least another 2000 s, allowing infiltration to occur to establish a fully developed metal flow and solid shell growth conditions. Input data consisted of materials properties for slag and metal \((T_{slag}, T_{liquid}, \rho, \mu, \kappa, v_s, f, s, \Delta T)\).\textsuperscript{6,7}

In the present study 72 different runs were carried out on which each of the parameters listed in Table 1 was varied over an extensive range whilst the other parameters were held constant; the ranges used are also given in this table.

3. Results and Discussion

3.1. Typical Model Results

A typical result of bulk flow and phases developed in the meniscus after the calculations is presented in Fig. 2. It was previously mentioned that no assumptions were made regarding slag films and meniscus shape. Nevertheless, it can be seen that the model correctly predicts the formation a solid slag layer against the mould which would include the slag rim in the meniscus corner and the sintered layer on top of the slag pool. The formation of the thin shell of solidifying steel, along with the entrained liquid slag, is also correctly predicted. Interestingly, the growth of this shell is not limited to the vertical axis but its solidification front (shell tip) extends along the curvature radius produced by the interfacial tension between slag and metal. The shell tip can vary depending on the casting conditions from a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_c) (m/min)</td>
<td>0.6</td>
</tr>
<tr>
<td>(\eta) (dPa-s)</td>
<td>0.5</td>
</tr>
<tr>
<td>(T_{br}) (K)</td>
<td>1350</td>
</tr>
<tr>
<td>(\Delta T) (K)</td>
<td>20</td>
</tr>
<tr>
<td>(\rho) (c.p.m.)</td>
<td>60</td>
</tr>
<tr>
<td>(s) (mm)</td>
<td>5</td>
</tr>
</tbody>
</table>

* dPa-s means deci-Pascals per second, where 1 dPa-s = 1 Poise.
marked hook to almost a vertical shell. The effects of interfacial tension on meniscus curvature and shell tip have been explored in previous work. However, the current investigation is focused on the effects of the shell tip and gap formation on two critical phenomena during casting: 1, mould powder consumption (lubrication) and 2, the heat flux responsible for the formation of defects during solidification such as OM's.

These qualitative observations suggest that the model correctly predicts many of the natural phenomena occurring in the mould. Such phenomena have been discussed in previous publications and are shown here to highlight the role of macro-scale phenomena (such as bulk flow and phase evolution) on the local infiltration behaviour at the meniscus and finally on the formation of oscillation marks. Moreover, Fig. 2 also exemplifies the degree of resolution that is possible to attain in the simulations where the flow pattern at a large scale (rolls and jet) is connected to the phase map in the meniscus corner in a region of a few square millimetres and finally to the formation of defects (OM) of the order of tenths of a mm.

3.2. Sensitivity Study and Statistical Analysis

Point probes were located in key points within the mould to track the evolution of parameters such as pressure, temperature, $d_{\text{solid}}$, $d_{\text{liquid}}$, gap width $d_{\text{solid}}+d_{\text{liquid}}$, slag consumption, etc.). These key locations include, the mould exit, half mould length and more importantly, 45 mm below the meniscus level, where the peak heat fluxes and highest mould temperatures were predicted. The gap width is expected to be at a minimum (steel shell closer to the mould) at this peak flux location and hence it should also be a good indicative of powder consumption. As part of a comprehensive sensitivity study, the model was run 72 separate times, each with different casting parameters, allowing statistical analysis. For each of these 72 transient runs, statistics were collected at regular time intervals. Typical results for just one of these 72 runs is shown in Fig. 3, for the case $v_c=0.6$ m/min, $s=10$ mm and $f=60$ rpm (1 Hz) and a time lapse of just 5 cycles. As described before, the model runs transiently in time steps of 0.002 to 0.01 s (high $f$ require smaller time steps) and data were sampled for at least 50 s of simulation time (after steady state was reached at $\sim 1000–3000$ s). The data generated includes the evolution of heat flux, shell profiles, slag layer thicknesses, consumption, pressure and velocity in the gap for each run under every combination of casting conditions given in Table 1. A spreadsheet of typical results for each run includes 50–100 s of calculation time with up to 10000 data lines for the measurement of the parameters mentioned on each time step. These values were integrated and/or averaged to provide the overall peak heat flux values, total consumption, average OM depth and pitch for each run. A regression fit was produced for the peak heat flux and total powder consumption, while slag layer thicknesses, pressure and velocities are representative of the trends seen on each oscillation cycle. A complete description of the design of experiments, statistical analysis and regression fitting techniques can be found elsewhere.

3.2.1. Overall Powder Consumption

The effect of casting speed on powder consumption, $Q_s$, was explored by comparing the model results to the two most widely-used empirical relations, the Wolf and Ogibayashi equations. In both of these relations, $Q_s$ was reported to be an inverse function of slag viscosity ($\eta$) and casting speed ($v_c$). Wolf proposed $Q_s$ as a function of $1/\eta \cdot v_c$, whilst Ogibayashi suggested a dependency upon $1/\eta \cdot v_c$. A variety of fitting parameters were tested to produce the most physically meaningful behaviour as corroborated by Saraswat et al. Not surprisingly, the best fits to plant data were inverse correlations of viscosity to consumption similar, to Wolf's and Ogibayashi's terms, which implies that ($Q_s$) decreases when ($\eta$) and ($v_c$) increase. The
regressed equations based on Wolf’s and Ogibayashi’s terms are Eqs. (2) and (3) respectively.

\[ Q_s = \frac{0.82}{\eta^0.5 \cdot v_c} \] .......................... (2)

\[ Q_s = \frac{0.71}{v_c \cdot \eta} \] .......................... (3)

Slag viscosity and break temperature in the runs were selected using properties from an empirical method for optimum casting according to Mills et al. A Figure 4 presents the comparison of plant measurements, prior numerical models and the predictions in this work with the regressed Eqs. (2) and (3).

From this point on, the equation deduced from Wolf’s term was chosen since it provides a better agreement to the reported plant data under low and high viscosity conditions, while the equation based on Ogibayashi’s term tends to under-predict consumption at high powder viscosities (Fig. 4). Furthermore, extrapolation to higher casting speeds is presented in Fig. 5 in order to test the flexibility of the chosen equation for powder consumption. In this case, slag viscosity data from Kawamoto et al. \((\eta = 0.8 \text{ dPa-s})\) were inserted into Eq. (2) for casting speeds up to 9 m/min. The results in Fig. 5 show excellent agreement with the data reported. This both shows that the model derived Eq. (2) matches existing plant data, without the need for any fitting parameters, and agrees with current plant practice that slag viscosity should be reduced as casting velocity increases to increase consumption.

Despite the fact that the overall consumption results from Eq. (2) are in excellent with the experimental data, it should be pointed out that the consumption is based on measurements at a reference point on the midpoint of the narrow face. This implies that a 3D model is required to determine the powder consumption distribution along the mould width.

3.2.2. Powder Consumption during the Oscillation Cycle

It can be seen from Fig. 3 that the pressure in the channel (at its thinnest point) is low during \(t_n\). This low pressure in the channel effectively draws molten slag into the gap, and thereby results in the formation of a slag film. The powder consumption \(Q_s\) (kg/m²) was calculated from the mass flow rate, \(Qc\) (in kg/s) which can be readily transformed into \(Q_s\) (kg/m²) using the relation \(Q_s = 2(w+t) \cdot v_c \cdot Q_c\), where \(w\) and \(t\) are the width and thickness of the mould. Inspection of the pressure in Fig. 3 shows that:

- \(Q_s\) (and \(Q_c\)) are at a minimum at the start of \(t_n\) \((t_n^n)\).
- There is a rapid increase in \(Q_s\) from midway through \(t_n\) \((t_n^m)\) into early part of \(t_p\); maxima in \(Q_s\) occurs in \(t_p^e\) when the liquid slag is thick, the flow direction of molten slag is partially downwards and the pressure is low.
- There is a gradual decrease in \(Q_s\) through \(t_p\) as the slag flow changes from downwards to horizontal. The pressure increases with \(Q_s\) reaching a minimum at \(t_p^e\).

It can be observed that there is a 3-fold variation in \(Q_s\) during the oscillation cycle compared with a 2-fold variation in \(d_{\text{liquid}}\). This occurs because \(Q_s\) and \(Q_c\) are principally determined by \(d_{\text{liquid}}\), but are also affected by both the direction and velocity of the slag flow.

3.2.3. Peak Heat Fluxes \((q_{\text{peak}})\)

The results shown in Fig. 3 are typical of all the 72 runs carried out in this study. Inspection of the heat fluxes in Fig. 3 indicates that:

- \(q_{\text{peak}}\) is at a minimum at the start of \(t_n\) \((t_n^n)\).
- There is a steady increase in \(q\) from \(t_n\) start into early part of \(t_p\) \((t_p^m)\). The maximum for \(q\) occurs in \(t_p^e\); this behaviour is attributed to the convective cooling supplied by slag flowing over the shell, when the slag flow in the channel changes from horizontal to downwards in early \(t_n\) (mould starting to descend).
- There is a gradual decrease in \(q_{\text{peak}}\) through \(t_p\) until it reaches a minimum at \(t_p\) end or \(t_p^n\) start.
- There is a 4% variation in heat flux through the oscillation cycle, which is similar in magnitude to the variations in \(d_{\text{solid}}\) suggesting that variations in heat flux are principally due to the variations in \(d_{\text{solid}}\).

3.2.4. Effect of Casting Speed

The heat flux data generated in the sensitivity study were found to increase as the casting speed \((v_c)\) increased (Fig. 6) as shown in a previous publication. \(^6\)
3.2.5. Effect of Interfacial Resistance and Break Temperature

The apparition of an interfacial resistance \( r_{\text{int}} \) or contact resistance is a consequence of the high cooling rates that the liquid slag undergoes during infiltration. This rapid cooling produces a predominantly glassy slag accompanied by shrinkage which results in an interfacial resistance \( r_{\text{int}} \) or “air gap”. Thus, the overall resistance to thermal flow between shell and mould is given by:

\[
\frac{1}{r_{\text{total}}} = \left( \frac{d}{k} \right)_{\text{solid}} + \left( \frac{d}{k} \right)_{\text{liquid}} + r_{\text{int}} \tag{4}
\]

where \( d \) and \( k \) are, respectively, the thickness and thermal conductivity of the slag film layers. In practice, the \((d/k)\) term for the liquid layer has little effect since the thickness is less than 10% of that of the solid and it can be said that the heat transfer is mainly controlled by \( d_{\text{solid}} \). The break temperature \( T_{\text{br}} \) determines the thicknesses of the solid and liquid layers, where an increase in \( T_{\text{br}} \) will increase \( d_{\text{solid}} \) and decrease \( d_{\text{liquid}} \). Figure 3 shows that the liquid slag thickness follows the same trend as the heat flux, thus, the liquid film increases at the expense of the solid slag layer and vice versa. In reality, the factors which affect both crystallisation (e.g. CaO/SiO\(_2\) ratio of flux) and \( r_{\text{int}} \) would also tend to increase \( T_{\text{br}} \) and consequently \( d_{\text{solid}} \). For this reason the interfacial resistance and \( T_{\text{br}} \) have been linked through Eq. (4) in this work. This relation was obtained by plotting reported data for \( r_{\text{int}} \) \(^{19-21}\) as a function of the (CaO/SiO\(_2\)) ratio:

\[
r_{\text{int}} = 9 \times 10^{-5} (\text{CaO/SiO}_2)^{4.19} \tag{5}
\]

Data relating \( q_{\text{peak}} \) to the interfacial resistance are plotted in Fig. 6 for 4 different levels of \( r_{\text{int}} \) over a range of casting speeds \((0.6–2.4 \text{ m/min})\).

It can be seen that the magnitude of the interfacial resistance has a major effect on the heat flux. A best fit of the heat flux data generated by the present model was carried out and the effect of viscosity was explored using various regression terms: e.g. \( \eta^{0.5} \), \( 1/\eta^{0.5} \), \( v/\eta^{0.5} \), \( v/\eta \), \( v \). The best fit was obtained with \( v \cdot \eta^{0.5} \) (the reciprocal of Wolf’s term) and was used to deduce the following relationship based on the model results:

\[
q_{\text{peak}} = 0.57v_c \cdot \eta^{0.5} + \frac{0.000249}{r_{\text{int}}} \tag{6}
\]

This relation implies that the slag film thickness \( (d_{\text{film}} = d_{\text{solid}} + d_{\text{equil}}) \) is an inverse function of viscosity \((i.e. d_{\text{film}} \propto 1/\eta^{0.5})\). Figure 7 shows good agreement with the heat flux values calculated with this equation to values recorded in plant by Suzuki \( ^{22}\) (Fig. 7(a)) and also good agreement with thin slab data reported by Hanao \( ^{23}\) (Fig. 7(b)). Although Hanao \( ^{23}\) reported plant data for a rather narrow viscosity range; the data is consistent with Eq. (6), since increasing \( \eta \) (i.e. decreasing \( d_{\text{film}} \)) resulted in increasing \( q \). The powder properties used in these case studies correspond to the slag viscosities and CaO/SiO\(_2\) ratios reported, which were used as inputs for Eq. (5) to calculate \( r_{\text{int}} \).

3.2.6. Shell Solidification

Although shell growth was calculated throughout the whole mould length, we will examine the just two points for validation where previously published data exists; these are located at the mould exit and 45 mm below the meniscus surface where the peak heat flux occurs. The model predictions at these 2 locations compared to measurements reported by Hanao \( ^{23}\) for thin slabs and with Thomas \( ^{24}\) and Zhang \( ^{25}\) for conventional slabs in Figs. 8(a) and 8(b), respectively. Although the shells calculated are 25% below the measurements due to Thomas \( ^{24}\) and the simulations due to Meng \( ^{11}\) the predictions are in good agreement with the measured values by Hanao \( ^{23}\).
and lie just 10–15% below the measurements cited by Zhang et al.25) These results are representative of the accuracy of the present model predictions.

3.3. OM Formation

Predicted slab profiles were assessed by placing a fixed point probe at the \( q_{\text{peak}} \) location 45 mm below the meniscus. The profiles generated exhibit regularly-spaced indentations similar to oscillation marks. The pitch of these indentations (\( l_{\text{OM}} \)) was determined and compared with the theoretical pitch of oscillation marks (\( l_{\text{OM}} = \frac{v_c}{f} \)) in Fig. 9 where it can be seen that the pitch of the indentations agree perfectly with the theoretical pitch of oscillation marks.

Furthermore, the profile of these indentations maintains a close resemblance to experimentally measured OM’s, as shown in Fig. 10. In this figure the oscillation marks predicted by the model are compared with those reported by Badri et al.26,27) using a bench-top continuous caster. Note that the pitch of the OM’s in the experiments and simulations were normalised through the oscillation shape to allow direct comparison.

It can be seen from the shell profile predictions in Fig. 10 that:

- The depth of indentation is small in initial stages of \( t_n \) when the mould and slag rim start their descent.
- The depth increases sharply around the mid-way through \( t_n \) (\( t_{n,\text{mid}} \)).
- The maximum depth of indentation occurs at the end of \( t_n \) (\( t_{n,\text{end}} \)) when mould and rim are at their lowest position.
- The depth of indentation decreases rapidly in the early stages of \( t_p \) and more gradually through the later stages of \( t_p \).
- The heat flux increases steadily through \( t_n \) with a peak in early \( t_p \) in both the model and Badri’s experiments.26,27)

3.3.1. Effect of Frequency on Oscillation Marks

The shell profiles predicted by the model are shown in Fig. 11. The pitch (\( l_{\text{OM}} \)) of the indentations predicted by the model was found to decrease with increasing frequency (\( l_{\text{OM}} = \frac{v_c}{f} \)) as well as the depth of the indentations (\( d_{\text{OM}} \)), which is in line with plant observations. It can also be seen from Fig. 11 that the shape of the oscillation marks is much...
closer to that predicted by the model than those derived with the Bikerman equation.

3.3.2. Effect of Negative Strip Time on Oscillation Marks

It is well-established that \( d_{OM} \) increases as the negative strip time and % negative strip increase. The average \( d_{OM} \) shown in Fig. 11 was plotted as a function of \( t_n \) for the different frequencies (i.e. stroke and casting speed were kept constant) and the results are shown in Fig. 12.

It can be seen that:
- In this case \( d_{OM}^{\text{init}} \approx 0.25d_{OM} \).
- The depth of indentation (\( d_{OM}^{\text{init}} \)) increases with negative strip time in line with the plant measurements.

Nevertheless, the depth of these indentations is just a fraction of the final marks, suggesting that the marks evolve into deeper defects in later stages. The predicted depths only account for 10 to 30% of those of typical oscillation marks. Thus, it is possible to conclude that these indentations are the origin oscillation marks and their depth can only increase with further solidification, shrinkage and accumulation of stress.

4. Conclusions

The model developed here makes no assumptions concerning slag films and meniscus shape in the continuous casting mould but correctly predicts the natural phenomena occurring in the mould such as the formation of slag films, slag rims, shell growth and oscillation marks onset. The model was used to derive a number of relationships between the casting parameters and responses, including:

(1) Powder consumption showed inverse relationships with casting speed and viscosity, producing an equation which provides good agreement with plant data without the use of external inputs such as plant measurements or empirical rules.

(2) Peak heat fluxes were found to be linearly dependent upon casting speed \( (\approx \eta^{0.5} \cdot v_c) \), in good agreement with plant data.

The model also predicted shell profiles with regular indentations along the slab surface which are hypothesised to be the onset of oscillation marks since their pitch, shape, relation with frequency, casting speed and negative strip dependency are identical to those of the theoretical pitch and plant observations for OM’s. Their depth decreased with increasing frequency and with decreasing negative strip time, in line with plant observations. However, the depth of these initial OM is considerably smaller than those recorded after casting indicating that the indentations may evolve into deeper marks after shrinkage and stress accumulation.

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Nomenclature

\[ d_{\text{liquid}}: \] Liquid slag film thickness \\
\[ d_{OM}: \] Depth of oscillation mark \\
\[ d_{\text{solid}}: \] Solid slag film thickness \\
\[ d_{\text{shell}}: \] Shell thickness \\
\[ f: \] Frequency (cycles/min) \\
\[ k: \] Thermal conductivity (W/m-K) \\
\[ q: \] Heat flux (W/m\(^2\)) \\
\[ Q_c: \] Mass flow rate (kg/s) \\
\[ Q_s: \] Powder consumption (kg/m\(^2\)) \\
\[ r_{\text{int}}: \] Interfacial resistance (m\(^2\)K/W) \\
\[ s: \] Stroke (m) \\
\[ T_{\text{br}}: \] Break temperature (K) \\
\[ t_n: \] Negative strip time \\
\[ t_p: \] Positive strip time \\
\[ v_c: \] Casting speed (m/min or m/s) \\
\[ v_m: \] Mould velocity (m/min or m/s) \\
\[ \eta: \] Slag viscosity at 1 573 K (dPa-s) \\
\[ OM: \] Oscillation mark \\
\[ SEN: \] Submerged entry nozzle

REFERENCES