HEAT TRANSFER IN A CONTINUOUS BLOOMCASTER

Four approaches to detecting disruptions to the primary cooling process in the continuous bloomcaster at BHP's Rod and Bar Division in Newcastle are investigated. Three of these are based on heat conduction models of the mould. A one-dimensional steady-state formulation leads to the conclusion that it may not be possible to detect changes in the length of the lubricating flux layer between the solidifying steel strand and the mould from data collected at thermocouples in the mould. Two two-dimensional models give formal procedures for determining either the heat input to the mould or the presence of hot spots in the strand from the thermocouple data. The final approach suggests the use of time-series analysis to detect changes in the heat transfer process.

1. Introduction

BHP Rod and Bar Division in Newcastle operates a four-strand bloomcaster which has an average production rate of 280 tonnes per hour. The machine is designed to cast continuously with downtime every fortnight. In this continuous casting process, molten steel flows from a vessel at the top of the caster through a nozzle into a 630mm by 400mm pool of liquid steel. This liquid is surrounded by a water-cooled copper mould, of depth 800mm, which oscillates vertically to facilitate the continuous process. The loss of heat from the steel causes it to solidify on its outer edges. As the steel descends, the layer of solid metal increases in thickness and the solidifying strand is continuously extracted from the mould by a series of rollers. Finally, the strand is cut into workable lengths known as 'blooms'. To aid the casting process, specialized mould powders are added at the top of the mould. This powder melts and forms a lubricating layer between the solidifying steel and the mould wall. This flux prevents the steel from touching the mould and transmits heat from the steel into the mould (see Figure 1). The distance from the 'hot' face to the cooling-water channels is 16mm and the major part of temperature drop from the molten metal to the the water occurs across this distance. Heat flows from the liquid steel across the layers of solid steel casting, liquid and solid flux into the surrounding mould. Temperatures measured at the thermocouples, which are 13mm from the hot face of the copper mould, provide the main source of information about the heat transfer.

When the heat removal process is disrupted, the surface quality of the steel deteriorates, subsurface cracking may occur or, in the worst case, the steel shell

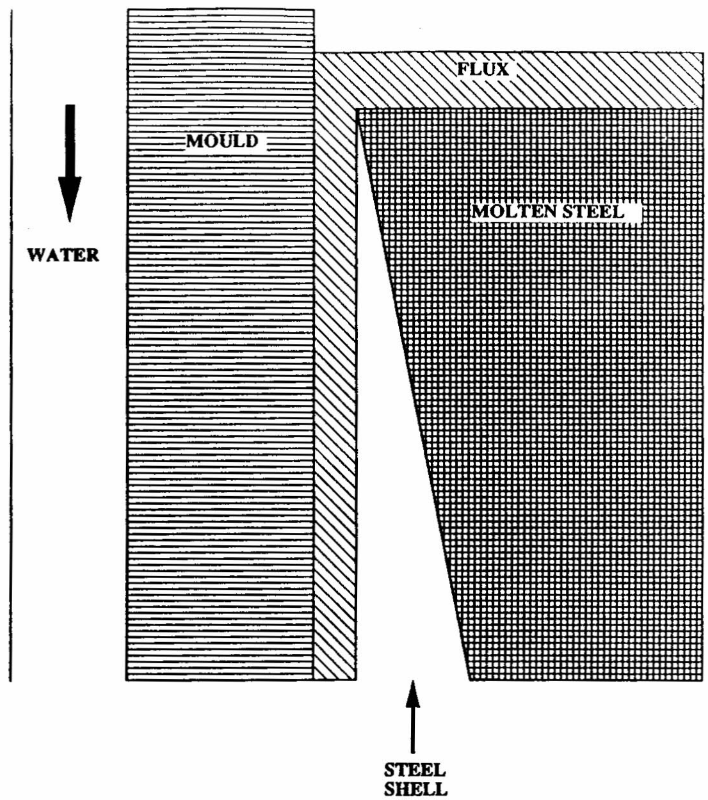

Figure 1: Diagram of the top of the bloomcaster.

at the bottom of the mould ruptures and a 'breakout' of molten steel occurs. When this happens the machine supports must be replaced at enormous cost in downtime and repairs.

The Study Group decided to examine the following specific aspects of heat flow in the copper mould

- a model for the detection of flux length changes
- a model for the detection of heat flow changes
- a model for the detection of hot spots moving with the strand
- time series analysis of the thermocouple data

All of these were addressed with an 'inverse flavour', that is, to see if it is possible to use the thermocouple data to infer information about the heat flow.

2. A model for the detection of flux length changes

As described above, the flow of flux down the sides of the solidifying steel is essential to the operation of the caster (Bland, 1984; Fowkes & Woods, 1989). Since the flux provides a highly conductive path for the heat, one of the disruptions to the normal flow of heat occurs when the layer of flux between the solidifying steel and the mould is broken. If the flux layer is broken, the heat transfer must occur across a layer of air which has relatively high thermal resistance and a 'hot spot' is likely to form. When this spot eventually descends to the exit of the mould, the thickness of the shell may not be enough to support the liquid steel in the interior of the strand and a breakout may occur. The flow of flux will affect the length of the flux column. We addressed the question

' How does the length of the flux zone influence the temperature readings in the copper mould?'

The simplest model that displays the required features is shown in Figure 2.

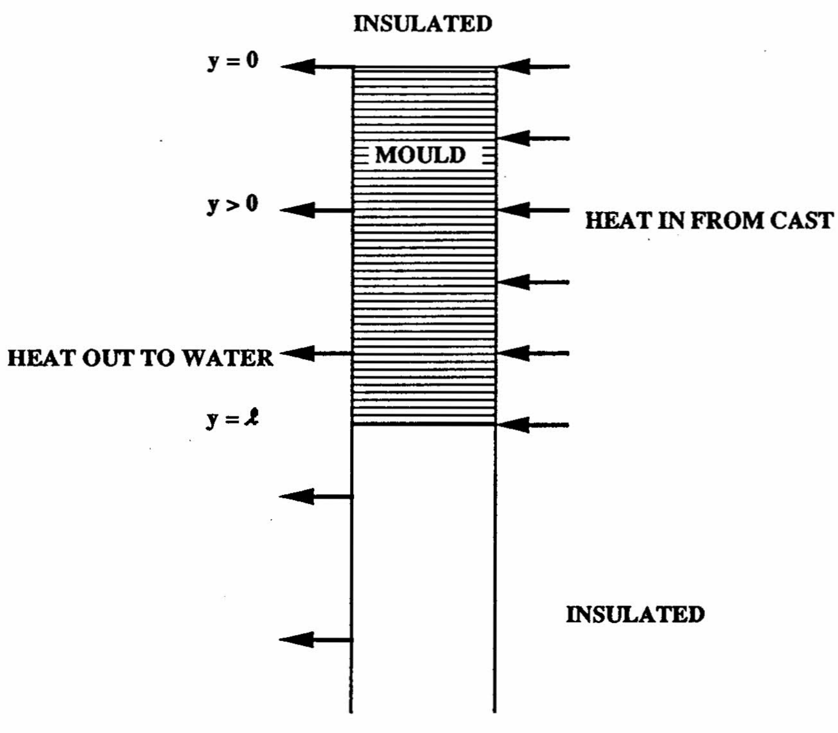

Figure 2: A schematic diagram of the copper mould.

Since the mould is 16mm thick and 800mm deep, this model assumes that the mould is one-dimensional and semi-infinite ($y \geq 0$) with uniform heat input from the steel over a region $y = 0$ to ℓ. We assume that this is the length of the intact flux layer and that there is no flux below this level in the mould so that by comparison with the fluxed region the heat transfer is negligible. The heat flow through the top of the mould is also taken to be zero. We denote the heat flow to the mould from the cast by f and assume that the heat transfer from the mould to the cooling water takes place by convection with a heat transfer coefficient, per unit width of the mould, h. The appropriate one-dimensional heat conduction equation is

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial y^2} - h(T - T_w) + \begin{cases} f, & \text{if } y < \ell_1 \\ 0, & \text{if } y > \ell_1 \end{cases}$$

where ρ, c and k are the density, specific heat and thermal conductivity of the copper mould, respectively, and T_w is the water temperature, all assumed constant. The time-dependent form of this equation can be used to investigate the response time of the copper mould temperature to a sudden change of the flux length. A characteristic time-scale associated with a change in the flux length can be seen to be $\rho c/h$. A typical value of the heat transfer coefficient is 10,000 $Wm^{-2}K^{-1}$, the thickness of the mould is about 16mm and the density and thermal conductivity of copper are about 8954 kgm^{-3} and 386 $Wm^{-1}K^{-1}$, respectively, so that a characteristic response time is about 5.7 seconds.

A number of important features of the model can also be obtained from a steady-state analysis. The steady-solution of this problem is

$$T - T_w = \frac{-(f/h)}{[1 + \tanh(\sqrt{\frac{h}{k}}\ell)]} \frac{\cosh(\sqrt{\frac{h}{k}}y)}{\cosh(\sqrt{\frac{h}{k}}\ell)} + \frac{f}{h} \quad \text{for} \quad y < \ell$$

and

$$T - T_w = \frac{f}{h}\left[\frac{\tanh(\sqrt{\frac{h}{k}}\ell)}{1 + \tanh(\sqrt{\frac{h}{k}}\ell)}\right] e^{-\sqrt{\frac{h}{k}}(y-\ell)} \quad \text{for} \quad y > \ell$$

If the flux is in contact with the mould for all $y \geq 0$, we have

$$[T - T_w]_\infty = \frac{f}{h}.$$

Figure 3 shows typical temperature distributions calculated from this model. We see that a lowered temperature (from the infinite flux column case), with size dependent on ℓ, occurs over a length scale of order $\sqrt{k/h}$. We can examine

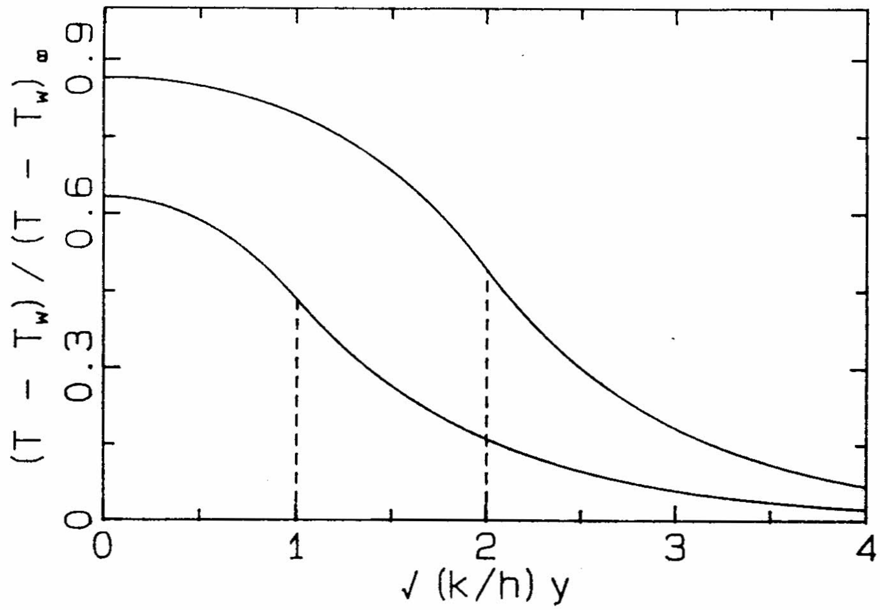

Figure 3: Scaled temperature distribution in the mould for two values of the fluxed region. The heat input from the cast lies between 0 and the dashed line in each case.

the effect of the flux length on the temperature difference, $T - T_w$, at the point x = ℓ. We see that

$$\begin{aligned} [T - T_w]_{x\,=\,\ell} &= \frac{f}{h}\left[\frac{\tanh\sqrt{\frac{h}{k}}\ell}{1+\tanh\sqrt{\frac{h}{k}}\ell}\right] \\ &= \frac{f}{h}.F \text{ say.} \end{aligned}$$

A plot of F versus $\sqrt{h/k}\ \ell$ is given in Figure 4. We conclude that if our observation is taken at the end of the fluxed region, then this will be half of the maximum temperature reached if flux is provided from $-\infty$ to ∞, since just half of all space is being provided with heat. We also note that if $\sqrt{h/k}\ \ell > 1$, we have little hope of detecting intact flux length changes from the temperature readings at the thermocouple probes. Using the typical values of the parameters given above, we can estimate that $\sqrt{k/h}$ is about 2.5 cm.

3. A model for the detection of heat flow changes

The Study Group also examined a two-dimensional model of the mould assumed to be of width a and depth b. The aim of this approach was to see if it

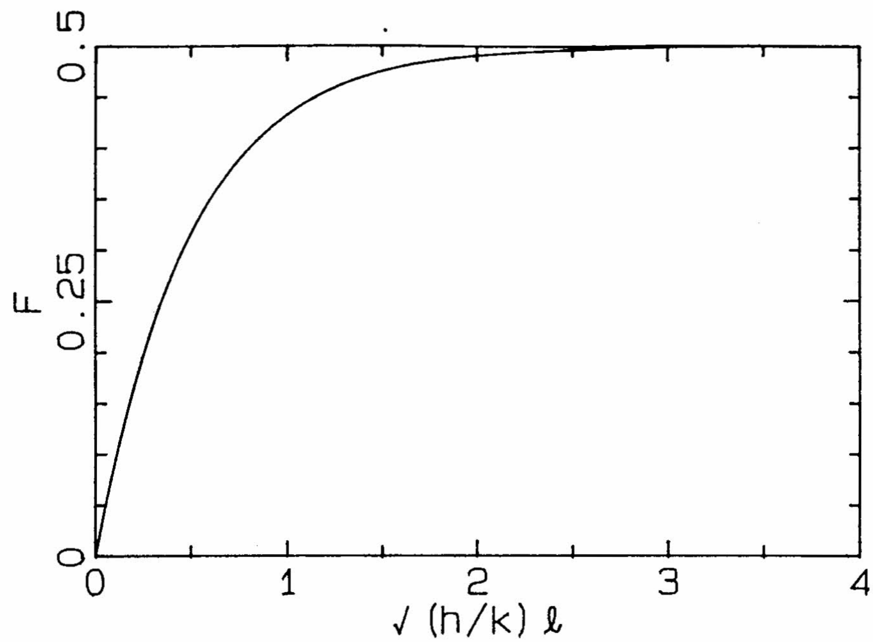

Figure 4: Fractional reduction in temperature at the end of the fluxed region.

was possible to estimate the temperature in the mould, and in particular at the thermocouples, given the heat flux at the hot face. The aim of this modelling was to use this model to solve the inverse problem associated with inferring the heat flux at the hot face from the thermocouple data. If this could be done rapidly and accurately then it might be possible to implement the inverse model 'on line' at the bloomcaster to detect the appearance of a hot spot in the mould and take appropriate action before the hot spot reaches the mould exit and thus avoid a possible breakout.

Consider a two-dimensional steady state model of the mould. We assume that the top ($y = b$) and bottom ($y = 0$) of the mould are insulated. We specify a heat flow at the hot face ($x = a$) and a convective cooling to the water at the cold face ($x = 0$). Thus we have

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \quad \text{for} \quad \begin{cases} 0 \le x \le a \\ 0 \le y \le b \end{cases}$$

with

$$-k\frac{\partial T}{\partial y} = 0 \quad \text{at} \quad y = 0, b$$

$$-k\frac{\partial T}{\partial x} = f(y) \quad \text{at} \quad x = a$$

and

$$-k\frac{\partial T}{\partial x} = h(T - T_w) \quad \text{at} \quad x = 0$$

where, as above, k is the thermal conductivity of the mould, h is the convective transfer coefficient for heat loss to the water, which is assumed to have uniform temperature T_w.

The solution to this problem can be found by separation of variables (Carslaw & Jaeger, 1959). It is given by

$$T(x,y) = B_0 + C_0 x + \sum_{n=1}^{\infty}\left(C_n \sinh\frac{n\pi x}{b} + B_n \cosh\frac{n\pi x}{b}\right)\cos\frac{n\pi y}{b}$$

where we have imposed the "no flow" conditions at the top and bottom of the mould and the constants B_n, C_n, $n = 0, 1, 2, \ldots$ are determined by the conditions at $x = 0$ and $x = a$. If

$$f(y) = \sum_{n=0}^{\infty} a_n \cos\frac{n\pi y}{b}$$

then

$$C_0 = \frac{-a_0}{k},\ B_0 = T_w - \frac{a_0}{h},\ C_n = \frac{hb}{kn\pi}B_n,$$

and

$$B_n = \frac{-a_n h}{\left(\frac{kn\pi}{b}\right)^2\left(\frac{nb}{kn\pi}\cosh\frac{n\pi a}{b} + \sinh\frac{n\pi a}{b}\right)}$$

If we assume a linear profile for the heat input at the hot face of the form

$$f(y) = -\left(1 + \frac{y}{b}\right)10^6 \quad \mathrm{W/m^2},$$

then we obtain the results shown in Figure 5, where we have taken the typical values of the parameters given above, together with the fact that the mould is 16mm thick and 800mm deep.

The inverse problem involves determining the input heat distribution from the temperatures recorded at the thermocouples. In terms of this model, we wish to estimate the coefficients a_n in the assumed expansion for $f(y)$ from the temperatures recorded at positions (x, y) in the mould. The thermocouples are a uniform distance from the hot face, and we denote their position by (x_p, y_i), $i = 1, 2, 3, \ldots, M$. We can then obtain a Fourier Series of the form

$$T(x_p, y_i) = \sum_{n=0}^{M-1} \hat{T}_n \cos\frac{n\pi y_i}{b}, \quad i = 1, 2, 3, \ldots, M.$$

This gives an M by M matrix equation for the unknown coefficients $\hat{T}_n$ in terms of the known temperatures.

By using the series solution for $T(x,y)$ given above, we are able to determine the first M Fourier coefficients, a_n, for the heat flow at the hot face. Once these coefficients can be determined, an estimate can be made of the temperature distribution in the whole mould.

Some preliminary work undertaken at the Study Group, and subsequently, indicates a number of problems with this approach, which is analogous to fitting polynomials to data. The results give large oscillations in the temperature distribution, while fitting the thermocouple data exactly.

An alternative approach is use a least squares method to fit a lower order solution to the thermocouple data. We write

$$\theta(x_p, y_i) = \sum_{n=0}^{N} \hat{T}_n \cos \frac{n\pi y_i}{b} \qquad i = 1, 2, 3, \ldots, M,$$

where N is less than $M-1$. The $\hat{T}_n$ are chosen to minimise

$$E = \sum_{i=1}^{M} \{T(x_p, y_i) - \theta(x_p, y_i)\}^2.$$

That is, the $\hat{T}_n$ ensure that

$$\frac{\partial E}{\partial \hat{T}_n} = 0 \quad , n = 0, \cdots, N.$$

It is possible that other fitting procedures would prove useful. The possibility of calculating the heat input to the mould 'on–line' makes the effort almost certainly worthwhile.

4. A model for the detection of a hot spot moving with the strand

This problem was aimed at developing a model which would allow the detection of a hot or cold spot moving with the strand, so that it is formally a time-dependent problem. We consider the mould to be infinite in extent in the y–direction. We assume that there is heat input given by the function $f(y - Vt)$ at the hot-face of the copper mould, where V is the speed of the moving strand, taken to be constant. We also assume convective cooling at the cold face and

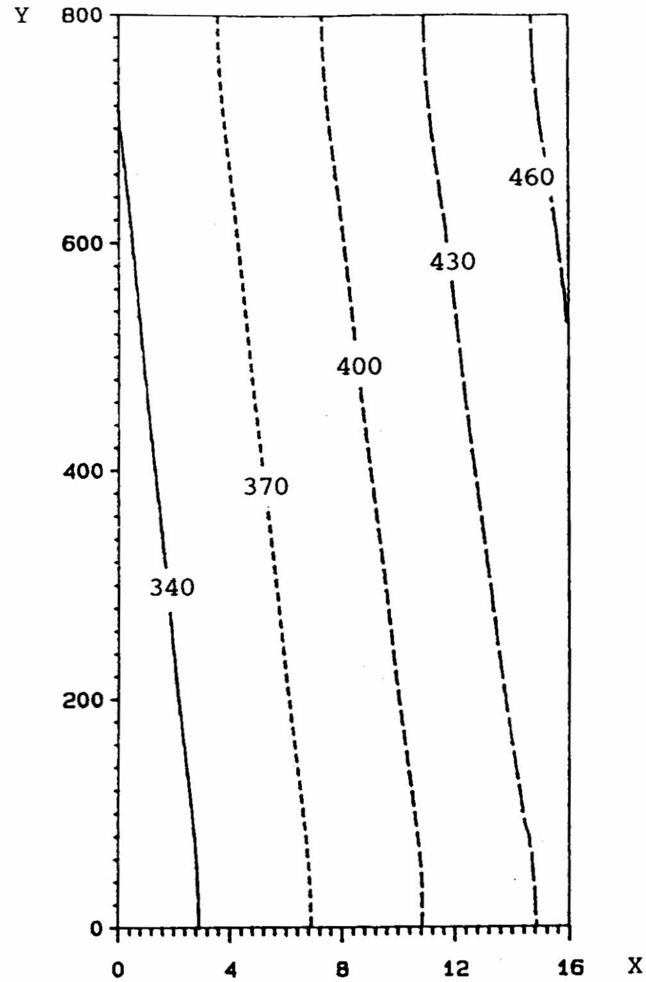

Figure 5: Contour plot of the temperature in the mould.

obtain the following equation:

$$\kappa\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) = \frac{\partial T}{\partial t}$$

where κ is the thermal diffusivity of copper, with boundary conditions

$$k\frac{\partial T}{\partial x} = h(T - T_w) \quad \text{at} \quad x = 0$$

and

$$k\frac{\partial T}{\partial x} = f(y - Vt) \quad \text{at} \quad x = d$$

where k is the thermal conductivity of the mould, h is the convective heat transfer coefficient and T_w is the water temperature, taken to be constant.

If we put $T' = T - T_w$, $h' = h/k, f' = f/k$ then we obtain

$$\kappa\left(\frac{\partial^2 T'}{\partial x^2} + \frac{\partial^2 T'}{\partial y^2}\right) = \frac{\partial T'}{\partial t}$$

with

$$\frac{\partial T'}{\partial x} = h'T' \text{ at } x = 0$$

and

$$\frac{\partial T'}{\partial x} = f'(y - Vt) \text{ at } x = d$$

We now solve this boundary-value problem using Fourier Transforms. We define

$$\overline{T} = \int_{-\infty}^{\infty} e^{i\omega y'} T'(x, y', t)\, dy'$$

where $y' = y - Vt$ and then $\overline{T}$ satisfies the equation

$$\kappa\frac{\partial^2 \overline{T}}{\partial x^2} - \omega^2\kappa\overline{T} = iV\omega\overline{T}$$

or

$$\frac{\partial^2 \overline{T}}{\partial x^2} = u^2\overline{T}$$

where $u^2 = \omega^2 + \frac{iV\omega}{\kappa}$.

The transformed boundary conditions are

$$\frac{\partial \overline{T}}{\partial x} = h'\overline{T} \quad \text{at} \quad x = 0$$

and

$$\frac{\partial \overline{T}}{\partial x} = \bar{f}(\omega) \quad \text{at} \quad x = d$$

where $\bar{f}$ is the Fourier Transform of f'. The solution of this boundary value problem is

$$\overline{T}(\omega, x) = K(\omega, x)\bar{f}(\omega)$$

where $K(\omega, x)$ is given by

$$K(\omega, x) = \frac{(u + h')e^{ux} + (u - h')e^{-ux}}{u(u + h')e^{ud} + u(u - h')e^{-ud}}$$

Formally, we can then invert the Fourier Transform to obtain

$$T'(x,y,t) = \frac{1}{2\pi i}\int_{-\infty}^{\infty} K(\omega,x)\bar{f}(\omega)e^{-i\omega(y-Vt)}\,d\omega$$

In addition, the problem of determining the heat flow into the mould from the temperature at any point can be solved formally as follows. Since

$$\bar{f}(\omega) = \frac{\overline{T}(\omega,x)}{K(\omega,x)}$$

then

$$f'(x,y,t) = \frac{1}{2\pi i}\int_{-\infty}^{\infty} \frac{\overline{T}(\omega,x)}{K(\omega,x)}e^{-i\omega(y-Vt)}\,d\omega$$

Both of these inversion formulae will require numerical methods and they are unlikely to be numerically satisfactory, but it should be noted that the original problem is ill-determined physically.

5. Time series analysis of the thermocouple data

BHP made a number of sets of temperatures obtained from the mould thermocouples available to the Group, and some preliminary analysis was carried out. It was suggested that it was very difficult to interpret the raw data directly and that a frequency decomposition of the power in the time series may reveal basic information about the original data. Using this technique it may be possible to detect features which are associated with a situation in which a breakout may occur.

6. Conclusions

Four approaches to detecting disruptions to the primary cooling process in the continuous bloomcaster at BHP's Rod and Bar Division in Newcastle have been investigated. Three of these, based on heat conduction models, have been studied in specific detail and the basic mathematical structure has been deduced.

Each of the two-dimensional detection models needs numerical implementation. Each is an inverse problem involving the indirect measurement of the quantity of interest, namely, the heat input to the mould or the presence of a hot spot in the strand, so that some form of stabilisation will be necessary for each.

The approach based on time-series analysis does not rely on any physical model but uses statistical methods to characterise the 'normal' or 'abnormal' functioning of the caster.

The implementation of these models is to be left to BHP.

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