British Steel : Oscillation Mark Formation in Continuous Casting

1. Introduction

This problem was a continuation of that presented at Heriot-Watt in 1988 and Oxford in 1989. Steel is continuously cast by being fed molten into the top of a copper mould and withdrawn from the bottom of the mould, at which point the outer part of the steel is frozen to form a solid shell. To lubricate the steel, a powder, flux or slag, is supplied at the top of the mould where it melts above the liquid steel (the steel being heavier). The liquid flux is drawn down between the mould and the steel through the effect of vertical oscillation of the mould; it is important that part of the cycle of oscillation is "negative strip", meaning that the mould is at the time moving down faster than the steel. The aim in 1988 was to understand better how the flux is actually moved down the mould and what governs the average rate of consumption of the flux. It is observed that the finished steel surface has oscillation marks in the form of regularly spaced notches as it comes out of the mould. The spacing of these indentations is given by the speed of the solid steel multiplied by the period of oscillation of the mould. The aim in 1989 was to understand the mechanism of how these notches are formed and what factors control their size and shape.

2. Previous work

The 1988 study (see also Fowkes and Woods) indicated that there is a thin lubricating layer of flux outside the steel extending from close to the top of the mould. The width of this layer can vary in the upper part of the mould due to the weakness of the steel adjoining the flux although scaling to obtain a pressure balance indicates that a typical width changes as $\sqrt{\mu}$ where μ is the viscosity of the liquid flux. The average consumption rate of the flux, whose flow was taken to be controlled by a flapping mechanism of the weak steel, is consequently also proportioned to $\sqrt{\mu}$.

The report of 1990 (also King et al.) invoked a similar model with a floppy steel membrane near the top of the mould but with the steel layer being totally rigid further down. Variation in the flux flow rate from one side of the point around which the steel hardens gives changing width of the flux layer and position of the final steel surface. This change in channel width again appears to scale width $\sqrt{\mu}$ (to get change in width $\propto$ flux flow rate $\propto$ typical channel width).

Both these results appear to be in conflict with experimental evidence which indicates that flux consumption and notch size decrease as the flux viscosity μ increases.

British Steel proposed an alternative mechanism for the formation of the oscillation marks. This was essentially thermal, rather than mechanical, with the indentations being created by an influx of relatively hot flux causing remelting of the outer edge solid steel near the top of the mould. The resulting liquid steel is taken to be pushed away by the flux. During the rest of the oscillation cycle, when the flux near the top is relatively cool, the steel/flux interface returns to its more usual position.

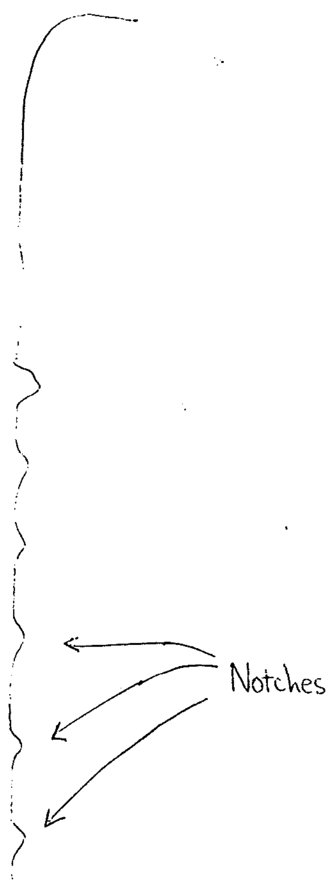
Some computational results based upon the Fowkes and Woods model of 1988 had also been obtained by British Steel. These gave a flux consumption which actually decreased, rather than increased, with μ. The difference is likely to be due to an assumption made earlier that the liquid flux channel is open at the bottom of the mould where pressure can then be taken to be atmospheric. The new results included the effect of narrowing of the gap due to solidification of the flux with the gap available for liquid flow closing up at a point clear of, and above, the base of the mould. Effectively the British Steel numerical results came from setting pressure to be atmospheric at a position a little way above that of zero channel width. Increasing viscosity of flux corresponds to decreasing its freezing point and thereby shortening the lubricating channel.

3. Further experimental information

Two items of experimental evidence unavailable at the Oxford study group were at hand.

One of these was a collection of photographs of the resulting frozen steel produced by suddenly stopping a continuous cast (ie. ceasing the supply and withdrawal of steel but continuing the cooling to totally freeze the steel). These show the oscillation marks in their final form below a certain level above which there is no evidence of such notches (see figure 1).

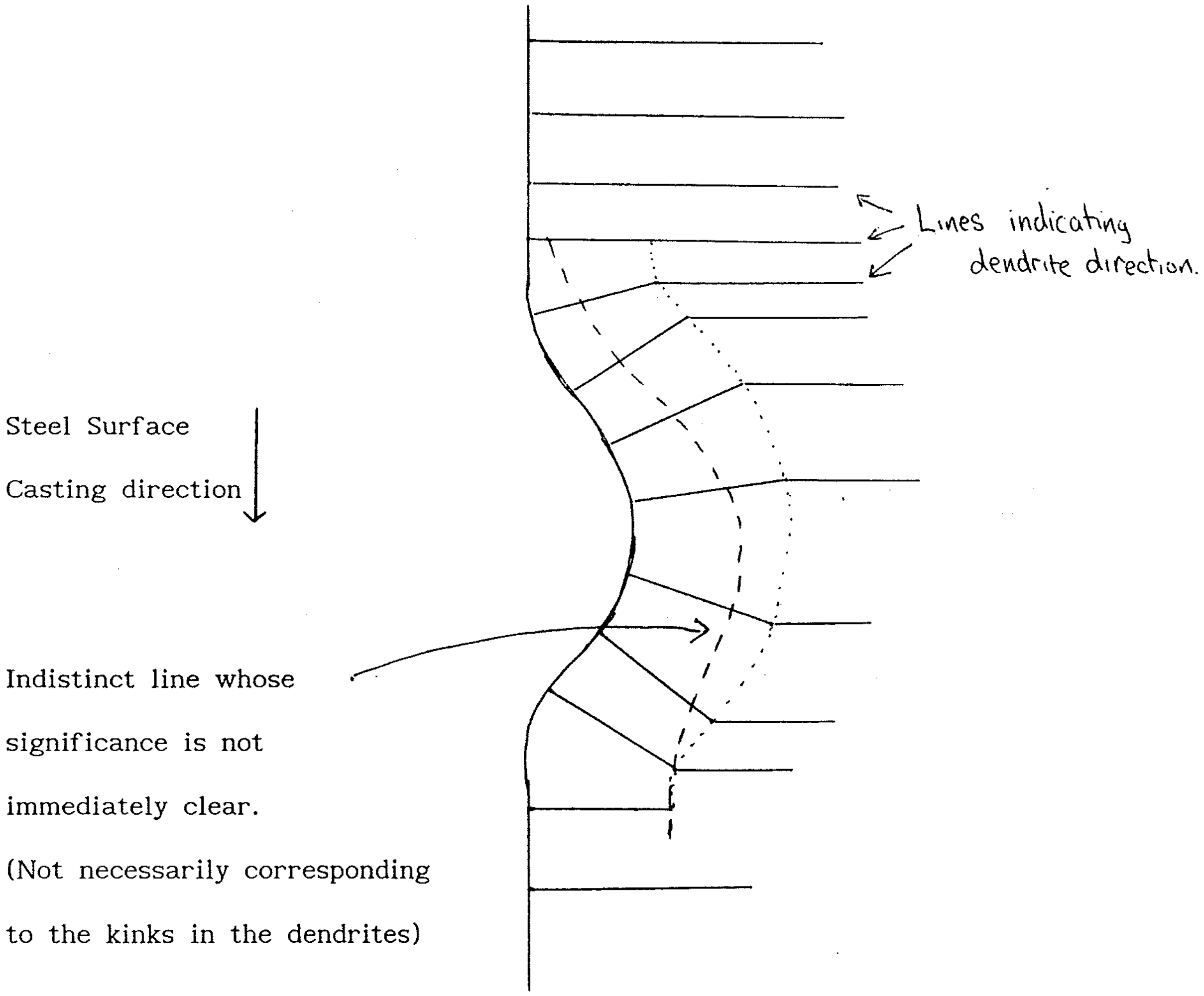
Figure 1. Typical steel surface resulting from stopping a continuous casting process.



These results appear consistent with the type of mechanical effect considered at Oxford in 1989.

The other item was another collection of photographs, this time of cross-sections cut through the steel in the vicinity of oscillation marks and indicating the local dendritic structure. Typically they show something of the form of figure 2 (Emi et al. ; see also Takeuchi and Brimacombe).

Figure 2 Dendrites in the solid steel near an oscillation mark.



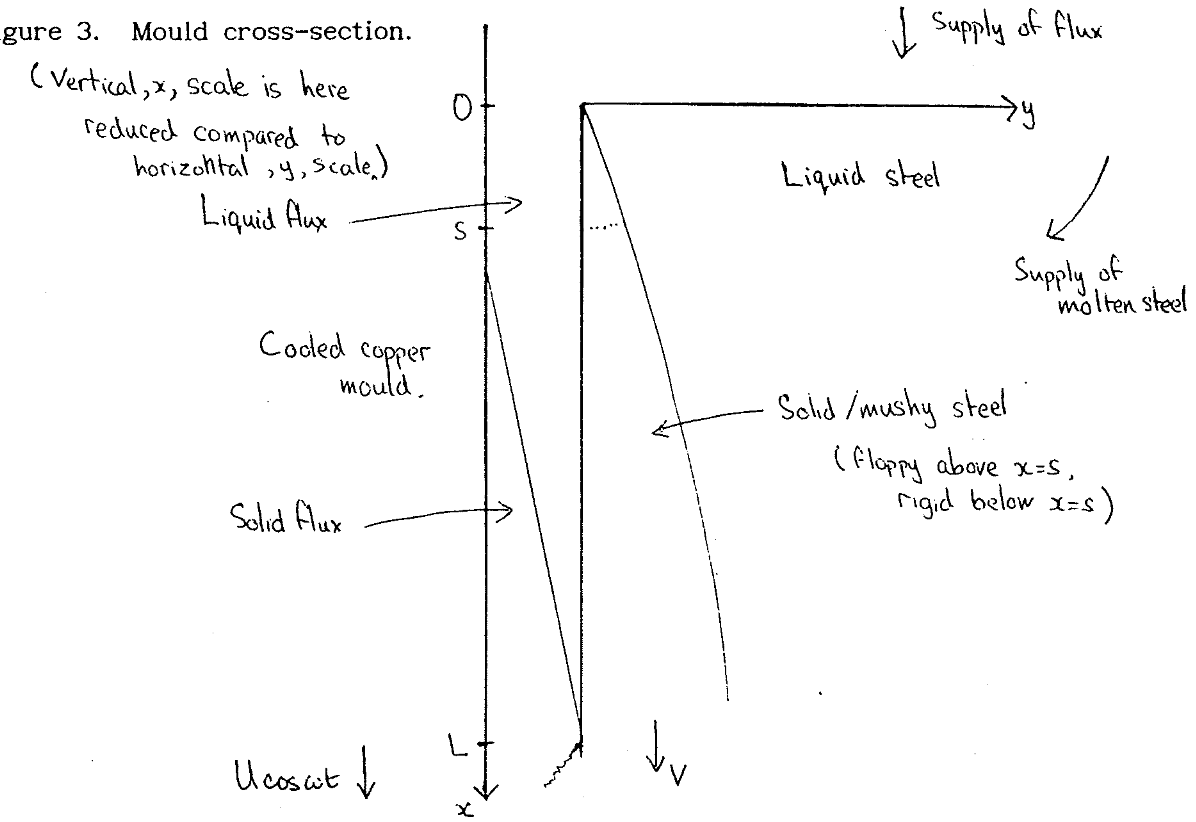
These pictures again suggest that the notches are formed mechanically (near the top of the mould if the position of change of direction of dendrites comes close to the steel surface but not if these corners remain well inside the steel).

One further reason for doubting a predominantly thermal cause for the oscillation marks comes from heat balance considerations. The amount of excess heat carried by flux being drawn into the gap from above during the period of negative strip (when the downward velocity of the mould, $U \cos \omega t$, exceeds that of solid steel, V) is only sufficient to melt steel to a depth of $\simeq 1/70$mm, assuming that the heat from the $\simeq$5mm length of flux is fairly evenly distributed over the top $\simeq$ 5mm of steel (about the length of an oscillation mark). Using a vertical length scale in the steel given by a diffusion length (but still using heat from $\simeq$5mm of flux) gave a similar distance of retreat for the solid steel surface. This surface variation is much smaller than the observed notch depth, $\simeq$1mm.

The result of all this evidence suggested a return to the type of mechanical model considered two years previously. We summarize this here.

4. Floppy steel skin model for mark formation

Figure 3. Mould cross-section.



We measure x vertically downwards from the upper surface of the steel and y horizontally from the mould surface.

Throughout the length of the flux channel, $0 < x < L$, which has total width h (mould surface is $y=0$, steel surface is $y=h$) there is conservation of mass of flux so, assuming negligible change of density,

$$Q_x + h_t = 0 \qquad (1)$$

where Q is the downward volume flow rate (per unit length around the mould) of the flux.

Taking the actual channel occupied by the liquid flux to have width H (so the solid/liquid flux boundary is at $y=h-H$ and the local width of the solid flux layer is $h-H$), classical lubrication theory gives the flow rate of liquid flux.

$$Q_L = \frac{H}{2}(U \cos \omega t + V) - H^3 p_x / 12\mu$$

where here p denotes pressure difference from hydro-(fluxo) static in the liquid flux; it is assumed here that the steel touching the flux is moving downwards with the known constant withdrawal speed of the solid steel, V. It is also assumed here that μ is constant. The solid flux is transported with rate

$$Q_x = U\,(h - H) \cos \omega t$$

so

$$Q = Q_s + Q_L = (h-H)\, U \cos \omega t + \frac{1}{2} H\,(U \cos \omega t + V) - H^2 p_x / 12\mu \qquad (2)$$

Below the point near which the solid steel becomes fully rigid, $x=s(t)$, the flux/steel interface just moves downwards with speed V so

$$h_t + V h_x = 0 \qquad \text{for} \quad x > s. \qquad (3)$$

Here thermal contraction of the solid steel and tapering of the mould have been neglected. For $s < x < L$ we now have a hyperbolic equation for h, substituting (2) and (3) into (1) gives an elliptic equation for p.

In the region where the steel layer is quite weak and floppy, ie. above $x = s$, pressure is simply given by that in the liquid steel (ferrostatic assuming that the steel, which has much lower viscosity than the flux, does not flow too rapidly).

$$p = (\Delta\rho)\ gx \quad \text{for} \quad x < s \tag{4}$$

Here $\Delta\rho$ denotes the difference between the flux and steel densities and g is gravitational acceleration.

For simplicity we suppose for the moment that there is no, or only a very small amount of, solid flux stuck to the mould in this region so $H = h$ and the flux flow becomes

$$Q = Q_L = \tfrac{1}{2}\ (U \cos \omega t + V)\ h - h^3 p_x\ /\ 12\ \mu \qquad x < s, \tag{5}$$

still assuming that the thin, floppy steel stain is drawn down with speed V.

(The alternative assumption of Fowkes and Woods was that the solid/mushy steel layer was also incapable of withstanding shear stress or tension so the viscous shear stress in the flux, μu_y, where u = vertical component of velocity, is zero at the flux/steel interface $y = h$. In this case we have the alternative flow rate

$$Q = h\ U \cos \omega t - 2\ h^3\ p_x / 3\mu \tag{5'}$$

A compromise model could be postulated that rate of stretching of the steel skin be proportional to the local shear stress exerted by the liquid flux, or the local tension within this steel layer.)

Now using (4),

$$Q = \frac{h}{2}\ (U \cos \omega t + V) - h^3\ \Delta\rho\ g/12\ \mu \tag{6}$$

and (1) yields a first order hyperbolic equation for h

$$[\frac{h}{2}(U \cos \omega t + V) - \Delta\rho\ g\ h^3/12\ \mu]_x + h_t = 0 \tag{7}$$

which has characteristics with local downward velocity

$$\dot{X} = \frac{1}{2}\,(U \cos \omega t + V - \Delta\rho\; g\; h^2/2\mu) \tag{8}$$

(Taking the alternative assumption of zero shear stress these are instead:

$$Q = h\; U \cos \omega t - 2\;\Delta\rho\; g\; h^3/3\mu\;, \tag{6'}$$

$$(h\; U \cos \omega t - 2\;\Delta\rho\; g\; h^3/3\;\mu)_x + h_t = 0, \tag{7'}$$

$$\dot{X} = U \cos \omega t - 2\;\Delta\rho\; g\; h^2/\mu. \tag{8'}$$)

At $x = s$, where the steel layer becomes fully rigid, we take pressure to be continuous (a significant change only being conceivable if the steel somehow gets very close to the mould near this point) :

$$[p] = 0$$

so

$$p_+ = \Delta\rho\; g\; s \tag{9}$$

(The subscript $+$ meaning the value taken just below this special point, that is, the limit taken as $x \to s+$. Similarly subscript $-$ will mean the value taken just above : $\lim_{x \to s-}$.)

For conservation of mass of flux

$$[Q] = \dot{s}[h] \tag{10}$$

so

$$\dot{s}\; h_+ - Q_+ = \dot{s}h_+ + h^3_+\; p_{x+}/12\mu - \frac{h_+}{2}\,(U \cos \omega t + V)$$

$$= \dot{s}h\_Q\_$$

$$= \dot{s}h_- + \Delta\rho\; g\; h_-^3\;/12\mu - \frac{h_-}{2}\,(U \cos \omega t + V)$$

or

$$(h_+ - h_-) [\dot{s} - \frac{1}{2} (U \cos \omega t + V)] = (\Delta\rho \; g \; h_-^3 - p_{x+} \; h_+^3) /12\mu \qquad (11)$$

As long as characteristics are directed into $x = s$ from one side and away to the other (9) and (11) should suffice at this point. With the expectation that s is nearly constant so $\dot{s}$ is small the characteristic in $x > s$ which move downwards with speed V will always be headed away.

Difficulty may arise if the characteristics just above, ie. for $0 < s - x \ll s$, also start to be directed away. In this case an extra condition must be imposed. This may be found by considering the mechanics of the steel skin more closely around $x = s$, perhaps modelling it as viscous beam. Another possibility may be for h_- to satisfy the natural boundary condition so that just above $x = s$ the characteristic velocity $\dot{X} \,|_{x=s}$ is $\dot{s}$:

$$h_-^2 = 2 \; \mu \; (U \cos \omega t + V)/g\Delta\rho - 2 \; \dot{s} \quad . \qquad (12)$$

A similar difficulty may arise at the top of the mould $x = 0$. If characteristics are moving up, $\dot{X} < 0$, no condition on h need be, or even can be, imposed. Otherwise a suitable requirement may again be a natural condition, the characteristics to have, locally, zero speed : $\dot{X} = 0$, i.e.

$$h^2_- = 2\mu \; (U \cos \omega t + V)/g \; \Delta\rho \text{ on } x = 0 \; . \qquad (13)$$

Again there is a possible alternative, namely that $h(0,t)$, which is the distance from the mould where the steel skin first forms, is fixed by the rate of cooling. However to use this would appear to require careful consideration of the local flow of the liquid steel.

To complete the coupled problem for p and h in $0 < x < L$ it remains to choose a pressure condition near the point $x = L$ where the channel closes up, ie. where $H \ll h$ and the solid flux fills virtually the whole of the gap between the steel and the mould. (We expect $x = L$ to be a point above the bottom of the mould. This is certainly given by British Steel's numerical calculations of the width of the solid flux layer and is consistent with the observation of pieces of solid flux coming out of the mould with the solid steel. It contrasts with the earlier supposition that there would be liquid flux at the base of the mould where pressure could be taken as atmospheric). At present it is far from clear what condition should be imposed here as this may depend strongly on how the solid flux breaks during the mould oscillation cycle.

To complete the model (assuming the difficulties with the above boundary conditions have been resolved) it remains to locate the transition point $x = s$ and determine the width $h - H$ of the solid flux layer. Where the steel layer becomes fully rigid (a floppy membrane or skin turns into a hard shell) needs knowledge of the mechanical properties of solid (or mushy) steel about its melting temperature. These are not well-known so all we can claim is that this point is likely to be given by the temperature of the steel layer and is, hopefully, nearly stationary. The first collection of photographs referred to above, §3, suggest that it is located below $x = 0$ at a distance of a few periods for the oscillation marks, equivalently a few amplitudes of oscillation (U/ω) of the mould.

5. Difficulties with the model

We again note that thermal contraction of the steel and tapering of the mould will cause modification of the model (e.g. to equation (3)). These effects may be crucial near the point of closure $x = L$ where vertical motion of the mould will cause significant variation in the width of the liquid flux channel H.

We also have the likely formation of shocks (and jump in h) in $0 < x < s$, where the governing equation is nonlinear and hyperbolic. It appears that if $x = s$ is substantially more than about one amplitude of oscillation from the top (or more precisely $s >$ maximum distance that a characteristic $x = X(t)$ can travel in a period $2\pi/\omega$) then unless h is constant for a large part of $0 < x < s$ shocks must appear in any periodic solution. (The photographs, §3 ,suggest such sufficiently large size for s .)

Another possible problem is the supposition that the steel layer always moves downwards with speed V . Clearly for this to happen the floppy layer must always remain under tension :

$$(V - U \cos \omega t) \int_0^x dx/h + (g\Delta\rho/2\mu) \int_0^x h \, dx \geq 0 \text{ for } 0 \leq x \leq s.$$

(It has been speculated that failure of this condition may correspond to formation of "hooks" in the steel near the oscillation marks.)

The supposition of constant flux viscosity can be dropped with μ being allowed to depend on temperature : $\mu = \mu(T)$. Such a modification was actually considered both by Fowkes and Woods and by British Steel.

6. Thermal problem for H

The temperature problem must also be solved to determine H through a free boundary problem for possible melting and freezing of flux and steel. A simplified model was considered during the study group using the high aspect ration to reduce it to a one-dimensional problem. The relatively high thermal conductivities were used to neglect the specific heat terms. It was also assumed that the steel could be modelled by a one-phase Stefan problem (either it is liquid at freezing temperature or fully solid).

Then T = temperature $= A_j + B_j y$ for $j = 1$ (solid flux) $0 < y < h - H$, $j = 2$ (liquid flux) $h - H < y < h$, $j = 3$ (solid steel) $h < y < h + w$, where w denotes the width of the solid steel layer (h, H, and w are all much smaller than L.) The coefficients A_j, B_j vary with x and t .

At $y = h - H$ the flux is at its melting point :

$$A_1 + B_1 (h - H) = A_2 + B_2 (h - H) = T_f.$$

At $y = h + w$ the steel is at its melting point :

$$A_3 + B_3 (h + w) = T_s.$$

At $y = h$ temperature is taken to be continuous and conservation of energy gives continuity of heat flux :

$$A_2 + B_2 h = A_3 + B_3 h,$$

$$K_F B_2 = K_s B_3 \tag{14}$$

where K_F, K_S are the thermal conductivities of flux and steel respectively. On $y = 0$ Newtonian (linear) cooling is assumed so that

$$K_F B_1 = S (A_1 - T_0)$$

where S is a heat transfer coefficient.

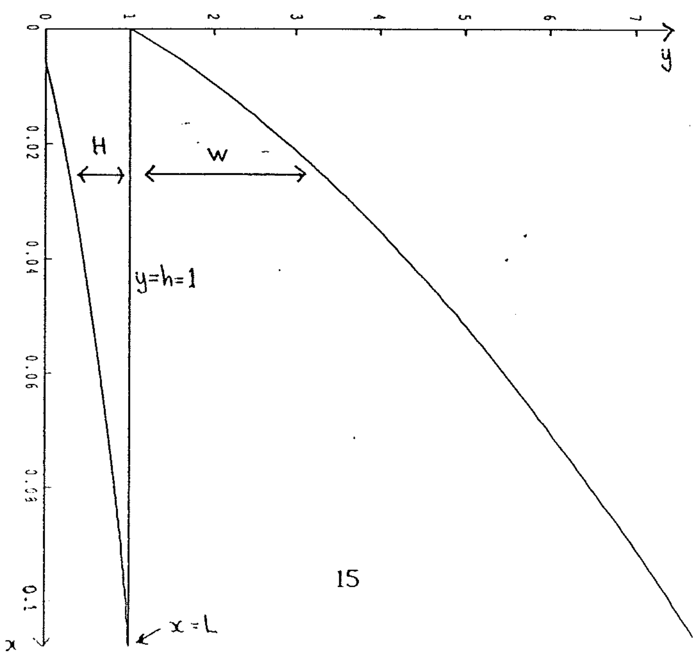
Finally, on the two free boundaries $y = h - H$, $h + w$ the jump in heat flux gives the speed of freezing (Stefan condition), so taking the appropriate convective derivatives :

$$\rho_F L_F [(h-H)_t + (h-H)_x U \cos \omega t] = K_F (B_1 - B_2),$$

$$\rho_S L_S (w_t + V w_x) = K_S B_3,$$

where L_F, L_S are the latent heats of flux and steel, and ρ_F, ρ_S are the densities of flux and steel respectively ($\Delta\rho = \rho_S - \rho_F$). A numerical calculation was carried out to find a periodic solution. Typical free boundaries (with x, y scaled differently) are shown in fig.4.

Figure 4. Graphs of $y = h - H$ and $y = h + w$ at some time taking a constant value of h (scaled to be one).



A more sophisticated model, allowing for radiative heat transfer directly from the steel surface to the mould has been solved by British Steel. This allows for the glassy nature of the flux and entails modification of eqn (14).

7. Notch prediction

A first attempt was made to solve numerically the problem (1), (2), (3), (7), (9), (11), (13), assuming the rather arbitrary condition $p = - \rho_F g x$ at a point just above $x = L$ (as predicted by the solution to the thermal problem §6). An arbitrary value for s and an initial condition were also chosen. However a shock formed immediately and computation ceased. (Ideally to predict the oscillation marks the program should be run until the solution becomes periodic).

An alternative approach, taking into account only a limited amount of fluid mechanics, was considered to get an idea of the possible size of the indentations. The key mechanism, of the notches resulting from a fixed in free boundary shape where a steel skin is bent and becomes very rigid, is essentially the same as for the more sophisticated model outlined above, §4.

Here h in the floppy region is assumed constant, taking a value h_0 which may be, say, thermally controlled. Then, neglecting gravity, pressure effects, and possible motion of the point $x = s$ where the floppy membrane becomes a rigid shell, we suppose that below the point $x = s$ the flow rate of flux is given by the average of the imposed velocities on either side :

$$Q = \frac{h}{2}(V + U \cos \omega t) \qquad x > s.$$

Above this point the hypothesis is made that the floppy skin cannot resist being dragged down by the flux so the steel has velocity = max (V, U cos ωt) and

$$Q = \begin{cases} \frac{h_0}{2} (V + U \cos \omega t) & \text{if } U \cos \omega t \le V \\ h_0 \, U \cos \omega t & \text{if } U \cos \omega t \ge V \text{ (negative strip))} \end{cases} \quad x < s.$$

Conservation of flux at $x = s$ then gives $Q_+ = Q_-$ so

$$\frac{h_+}{2} (V + U \cos \omega t) = \begin{cases} \frac{h_0}{2}(V + U \cos \omega t) & \text{for } U \cos \omega t \le V \\ h_0 \, U \cos \omega t & \text{for } U \cos \omega t \ge V, \text{ e.g. } |t| \le \phi/\omega \end{cases}$$

$$\text{where } \phi = \cos^{-1} (V/U) \quad .$$

(U is always made larger than V to ensure a period of negative strip.)

$$\text{Then } h_+ = \begin{cases} h_0 & \text{for } 2n\pi + \phi \le \omega t \le 2(n + 1)\pi - \phi \text{ (not negative strip)} \\ \dfrac{2 \, h_0 \, U \cos \omega t}{V + U \cos \omega t} > h_0 & \text{for } 2n\pi - \phi < \omega t < 2n\pi + \rho \text{ (negative strip)} . \end{cases}$$

The length of each oscillation mark is then $2V \phi/\omega =$

$\frac{2V}{\omega} \cos^{-1} \frac{V}{U}$, and has cross-sectional area

$$V h_0 \int_{-\phi/\omega}^{\phi/\omega} (\frac{2 \, U \cos \omega t}{V + U \cos \omega t} -1) \, dt$$

$$= \frac{2Vh_0}{\omega} [\cos^{-1} \frac{V}{U} + \frac{2V}{\sqrt{U^2-V^2}} \ln \frac{V}{U}],$$

and maximum depth $(U - V) h_0/(V + U)$.

For ϕ small, ie. $U \simeq V$, these become, approximately,

$$\frac{2}{\omega}\sqrt{2V(U-V)}\ ,\ \frac{h_0}{3\omega}\sqrt{\frac{2}{V}}\,(U-V)^{3/2},\ \text{and}\ (U-V)\,h_0/2V$$

respectively.

For quantities of the sizes given by British Steel the area is of the order of $1mm^2$.

References

1. T. Emi, H. Nakato, Y. Iida, K. Emoto, R. Tachibana, T. Imai & H. Bada, "Influence of physical and chemical properties of mold powders on the solidification and occurrence of surface defects of stand cast slabs", Proc. 61st. NOH-BOSC, 1978, 350-361.
2. N. Fowkes & A. Woods, "The flux of flux in continuous steel caster". Preprint, 1989.
3. J. R. King, A. A. Lacey, C. P. Please and P. Wilmott, "A note on the formation of oscillation marks in continuously cast steel." Preprint, 1990.
4. E. Takeuchi & J. K. Brimacombe, "The formation of oscillation marks in the continuous casting of steel slabs." Metallurgical Transactions B, 15, 1984, 493-509.

EJH, JRK, AAL, JL, DWS, RHT, DRW, PW.