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MOULD FLOW CONSIDERATIONS DURING THE CONTINUOUS CASTING OF STEEL

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ABSTRACT

Continuous casting of steel involves the solidification of molten metal to form a rectangular or circular section. This is achieved by pouring the liquid through a Submerged Entry Nozzle (SEN) into a bottomless water cooled mould and slowly withdrawing the solidifying strand.

The fluid flow characteristics in the mould are of fundamental importance to the quality of the cast products. This flow was studied by both observation of a water model and numerical analysis utilising a vorticity based formulation of the governing equations. From the physical modelling two counter rotating axial vortices originating at the bottom of the SEN were identified in the emerging jets. The effects of these vortices on the three-dimensional flow in the mould have been investigated using the numerical model.The major effects of this rotation are to push the inlet jets from the SEN exit ports downward, to spread the jets, and to alter the coupling between the circulation zones above and below the jet.

INTRODUCTION

Continuous casting is the most popular method of converting molten steel into solid sections suitable for further processing into commercial products. Steel is transported to a caster in large ladles from which it is poured into the mould via an intermediate vessel called the tundish. This is a bath shaped vessel which provides a buffer for ladle changes and allows impurities in the steel to float out. The tundish then supplies the casting mould with relatively clean steel through a bifurcated refractory nozzle. The nozzle, referred to as the Submerged Entry Nozzle or SEN, is essentially a vertical pipe with its lower end blocked and two horizontally opposed exit ports drilled just above the blockage. This arrangement creates two inlet jets which induce three dimensional flow patterns in the mould.

The casting mould is a water cooled copper device which cools the molten steel poured into it. The process relies on the solid shell which forms around the edges of the strand to be thick enough as it leaves the mould to withstand the ferrostatic head of the molten steel inside it. Powder, which is sprinkled on the steel meniscus, thermally insulates the surface as well as providing a lubricant between the shell and the mould wall. The mould is oscillated sinousoidally to prevent the shell sticking to the mould walls.

The flow in the mould is driven by the nature of steel delivery which is controlled by SEN design. The flow affects the stability of the meniscus and also the temperature distribution in the central molten region of the strand. Hence knowledge of the structure of this flow is extremely valuable in improving the performance of the continuous steel casting process.

Both physical and numerical modelling of the flow phenomena have been studied in the past. Herbetson, *et al* (1991) presented an excellent review paper which included descriptions of describe physical observations made from a clear plastic water filled model of the mould and SEN. This is feasible due to the similar kinematic viscosities of water and liquid steel. Dye injected into the flow revealed the flow patterns. Other measurable quantities such as SEN exit jet impact pressures on the relevant mould walls, and meniscus velocities and shapes were measured to allow the effects of different SENs and flow rates to be established.

A recent three dimensional numerical study of the flow field in the mould has been made by Flint, *et al* (1992). The equations were solved in primitive variable from using the TEACH computer program. A κ-ε turbulence model was used. Their model predicted a three dimensional flow field but the effects of the axial vorticity in the jets leaving the SEN, which had been observed experimentally by Heaslip *et al* (1987), were not discussed.

Flows in the SEN and mould have been investigated in this research by using a low Reynolds number one fifth scale model of a bloom caster and a laminar numerical model. The physical model confirmed that the jets leaving the SEN contained axial vorticity and the numerical study concentrated on assessing the significance of this vorticity and understanding the structure of the three-dimensional flow before introducing a turbulence model.

THE PHYSICAL MODEL

A one fifth scale clear perspex model of a bloom caster of cross sectional aspect ratio 1.575 (126 by 80mm) was constructed. The model was supplied by a header tank capable of maintaining steady flow for a considerable period. Flow rates were fixed by control valves above the model SEN and at the outlet of the model. The mould was sufficiently long to minimise the effect of the sump type outlet on the upper mould flow which was of interest. When steady flow at a particular flow rate was reached, dye was injected into the SEN enabling the flow patterns to be observed.

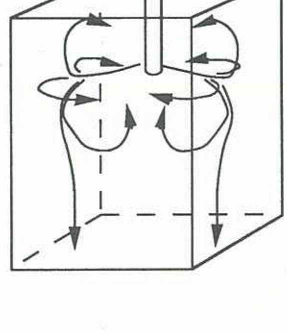


Figure 1. The orientation and intrinsically three-dimensional structure of the flow generated by the jets leaving the SEN.

Observations and Discussion

Flow in the mould was observed to be three-dimensional. The jets leaving the SEN were deflected by the faces of the mould to generate an intrinsically three-dimensional flow as shown in Figure 1. As the flow rate was increased, the flow became turbulent. The scale of the turbulence was initially large which effected the 'steady' nature of the dye transport considerably. When the flow rate was increased further, corresponding to Reynolds numbers found in a real caster, the turbulence scale decreased and the structure again appeared to be similar to that for laminar flow.

As recognised by others, (Flint *et al* 1991), the bulk of the fluid leaves the SEN through the lower portion of the ports due to the downwards momentum of the internal SEN flow.

The physical study revealed that the flow emerging from the lower halves of the SEN ports contains two counter rotating vortices. These are generated by the fast moving fluid in the centre of the SEN (due to the flow profile in the SEN pipe) striking the bottom of the SEN and moving both sideways and out of the port. This process may also be thought of as the redistribution of vorticity generated in the viscous boundary layers of the SEN upon reaching the exit ports. The axial rotation is visible in Figure 2 which is a view looking towards the SEN along the emerging jet.

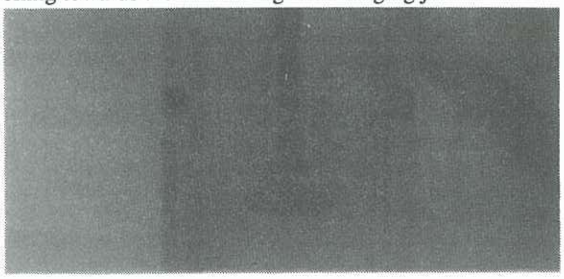


Figure 2. Evidence of two counter rotating axial vortices in the jets leaving the SEN.

The generation of the vortices within the SEN results in the movement of fluid from the centre of a jet out towards the edges of the port and then up the port walls. This continues after the jet leaves the port and eventually causes a bifurcation of the jet with one component moving upwards and the other downwards as shown in Figure 3.

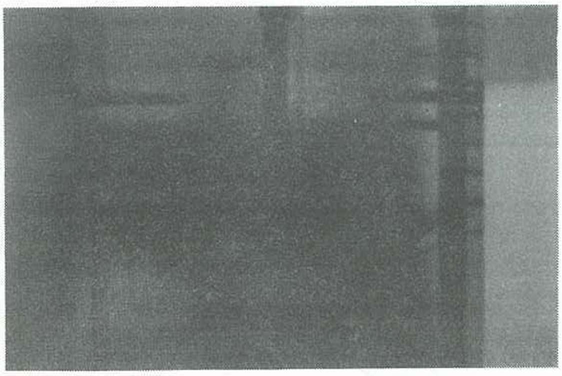


Figure 3. Bifurcation of the jet as a result of the axial vorticity.

THE NUMERICAL MODEL

The numerical model was based on the solution of the Navier-Stokes equations in vorticity - vector potential form. The velocity **V** was represented by a vector potential **A**,

$$\mathbf{V} = \nabla \times \mathbf{A} \tag{1}$$

The vorticity is the curl of velocity so that,

$$\zeta = \nabla \times \mathbf{V} = \nabla \times (\nabla \times \mathbf{A}) \tag{2}$$

As discussed in detail elsewhere (Harris 1992) the fluid motion can be represented by the equations,

$$\frac{\partial \zeta}{\partial t} = (\zeta.\nabla)\mathbf{V} + \mathbf{V}(\nabla.\zeta) - (\mathbf{V}.\nabla)\zeta - \zeta(\nabla.\mathbf{V}) + \frac{1}{Re}(\nabla^2\zeta - \nabla(\nabla.\zeta)) \tag{3}$$

$$\zeta = -\nabla^2\mathbf{A} \tag{4}$$

(Scaling has been chosen so that the Reynolds number in (3) is based on the average velocity of the fluid leaving the SEN and the semi-width of the caster in the direction of the jets.)

Equation (4) relies on **A** being solenoidal which is often assumed (e.g. Wong and Reizes 1984). We have fould that the application of solenoidal boundary conditions for **A** together with the calculation of a solenoidal ζ are necessary to ensure that **A** is solenoidal.

Similarly, the terms in (4) which involve the divergence of either ζ or **V** are usually omitted since ζ and **V** are solenoidal. Those in the terms representing vorticity convection were retained here to simplify the generation of conservative discretisations

Discretisation

A staggered mesh arrangement was used. The vorticity and vector potential components are located at the mid-points of the edges of the cells whereas the velocity components are located at the middle of the faces. This means that the conservation cells for the vorticity components are different from each other.

Both uniform and non-uniform grid spacings were used. The finite volume formulation was based on central differences except for the convection approximations which were made according to the QUICK scheme of Leonard (1979).

Boundary conditions

One quarter of the caster geometry was modelled by dividing the mould through the two centrelines of the SEN. As far as the mould was concerned, the SEN was considered to have zero width so that the incoming fluid entered via an inlet on one of the symmetry boundaries.

Free slip conditions were applied on the symmetry and surface boundaries and no slip conditions on the others. At the outlet the normal gradients of all variables were set to zero.

Boundary conditions for vorticity were derived directly from equation (2). Using properly formulated difference approximations for the derivatives appearing in the boundary conditions, it was found that the vorticity and, as a result, the vector potential were algebraically solenoidal.

Inlet Boundary conditions

The SEN port occupied a section of the x=0 symmetry plane. Boundary conditions for the vector potential were formulated in terms of an auxiliary potential following Hirasaki and Hellums (1968). This potential is normal to the inlet : the non zero component, B say, satisfies the Poisson equation,

$$\frac{\partial^2 B}{\partial y^2} + \frac{\partial^2 B}{\partial z^2} = -u_{in} \tag{5}$$

The components of the vector potential are then given by,

$$A_y = \frac{\partial B}{\partial z}; \quad A_z = -\frac{\partial B}{\partial y}; \quad \frac{\partial A_x}{\partial x} = 0, \tag{6}$$

where the last condition follows from the first two and the condition that **A** is solenoidal at the boundaries. Boundary conditions for (5) must imply a continuous vector potential across the edges of the inlet. u_{in} was chosen to be a biquadratic function extending over the bottom 60% of the SEN.

Rather than require specification of conditions for the tangential components of **V** to derive boundary conditions for the vorticity, the inlet axial vorticity, instead, was specified. This condition, together with the simplifying assumption that the flow entering the caster was fully developed allowed the tangential components of velocity to be evaluated indirectly. The assumption of a fully developed velocity field implies that,

$$\frac{\partial u}{\partial x} = 0 \qquad (7)$$

and specification of ζ_x allows v and w to be evaluated using

$$\frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} = -\frac{\partial \zeta_x}{\partial z}; \quad \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} = \frac{\partial \zeta_x}{\partial y} \quad . \qquad (8)$$

where ζ_x is the axial component of vorticity at the inlet. Equations (8) can be solved to yield the tangential v and w at the inlet so that the vorticity boundary conditions can be applied via equation (2) in the usual way. In practice, a separate computer program was used to calculate the tangential velocity components from a specified axial vorticity distribution.

The inlet vorticity distribution was specified by adjustment until a realistic velocity field was calculated. The strength of the rotation was considered to be measured by the total circulation over the inlet relative to the mass flux through it. The vorticity distribution (Figure 4) was multiplied by various values (VM = 0,1,2, and 4) to study the influence of the strength of the vorticity on the effects induced in the flow. A numerical model of the flow in the SEN (Harris 1992) was used to check the appropriateness of the distribution. This model produced axial vorticity having an average strength (as indicated by the ratio of circulation to mass flow) corresponding to a vorticity multiplier of 3.85.

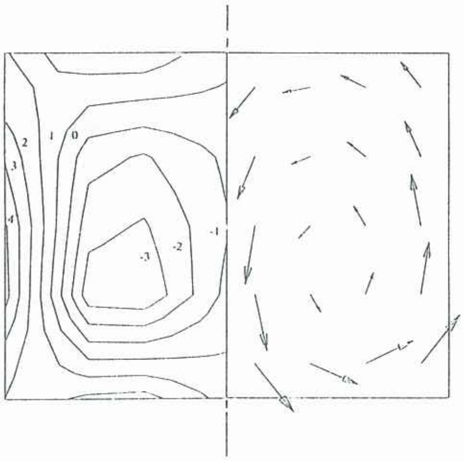
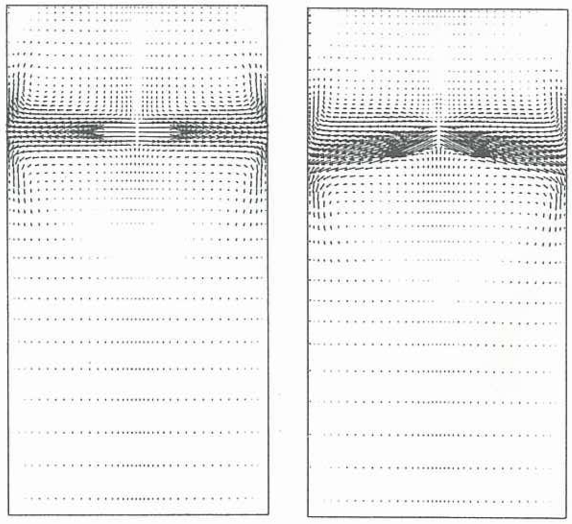


Figure 4. Normal vorticity and tangential velocity fields applied with various scale factors to the bloom mould geometry.

Results and Discussion

Velocity vector maps on the centre plane of the SEN (y=0) are shown in figure 5 for the solutions with no axial vorticity and for VM=4. The map with no axial vorticity indicates that the jets leaving the SEN do so horizontally since there has been no downwards momentum applied at the inlet. The map for the flow with vorticity indicates that the jets are deflected downwards.



(a) (b)

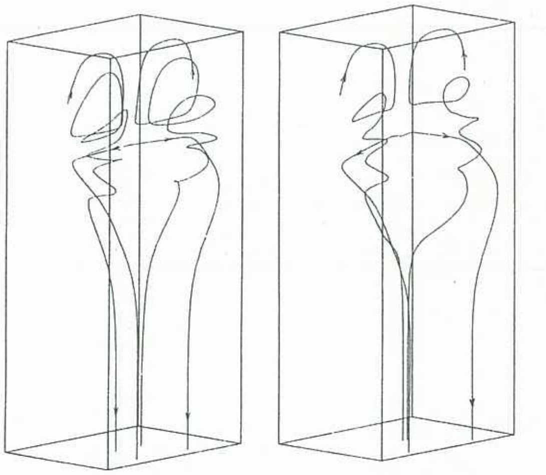
Figure 5. Vector maps through the centre plane of the SEN with (a) no axial vorticity and (b) axial vorticity with VM = 4.

The maps in Figure 5 are in line with conventional understanding of the flow in the mould based on an essentially two-dimensional reasoning. The bulk of the flow in the jets is deflected by the walls and streams downwards towards the exit. In each half of the mould there are two regions of recirculation. The upper recirculation is particularly important since it provides the mechanism by which impurities or inclusions are spread through the mould.

The flow field is, however, three-dimensional as evidenced by the streamlines in Figure 6. Considering the flow with no inlet vorticity first, the upper and lower regions of recirculation are not separate but are part of a coupled toroidal motion. Streamlines which start in the upper recirculation zone spiral around the axis of the toroid down and around the jets through the 'lower recirculation' and finally feed the central region of the flow leaving the mould. The jets pierce the toroid, are deflected by the wall and feed the wall regions of the outlet.

This simple observation is significant in that it indicates that inclusions have a direct path from the top of the mould to the centre of the strand.

In terms of flow structure, the effect of the axial vorticity is to stretch the toroid downward towards the exit of the mould.



(a) (b)

Figure 6. Streamlines showing the three-dimensional coupling between the upper and lower recirculation zones for (a) no axial vorticity and (b) axial vorticity with VM=4.

The stretching of the toroid is due to the change in angle of the fluid jet entering the mould. The angle between the jet and horizontal changes from 0 to 2 to 4 to 8 degrees with scale factors of 0,1,2 and 4 respectively. This is directly related to the axial vorticity. The horizontal velocity inlet profile, being biquadratic, forces most of the incoming fluid to exit the port near the SEN centre line. Here the tangential inlet conditions force the jet downward, the angle depending on the magnitude of the inlet vorticity . Nearer the edge of the jet the flow travels upward out of the port.

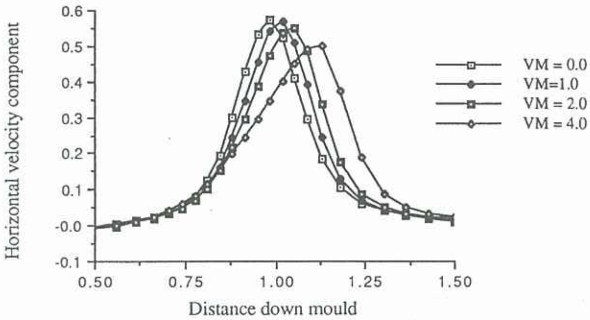


Figure 7. The horizontal velocity component distribution midway between the SEN outlet and the narrow face. (VM is the inlet axial Vorticity Multiplier)

The horizontal velocity profile midway between the SEN outlet and the narrow face is shown in figure 7. As the inlet vorticity is increased the jet profile moves further down the mould as discussed above. The jet also becomes more diffuse. This is evident from the decreasing peak velocity and broadening of the velocity profile. The probable mechanism for this behaviour is the axial rotation of the jet forcing fluid to move away from its centre line, hence lowering the horizontal mass flux and dissipating momentum.

Horizontal velocity profiles near the narrow face are plotted against distance down the mould on figure 8. The same trends as those discussed above are more evident at this location as the jet strength has had more time to dissipate. The consequences of this for casting of steel are important. Lowering of the impact point may cause excess shell thinning which at worst could result in a breakout. This is offset by the reduction of the peak impact velocity. The spreading of the SEN exit jet is also advantageous for inclusions to rise to the surface of the mould as the their buoyancy forces are more significant in slower moving fluid.

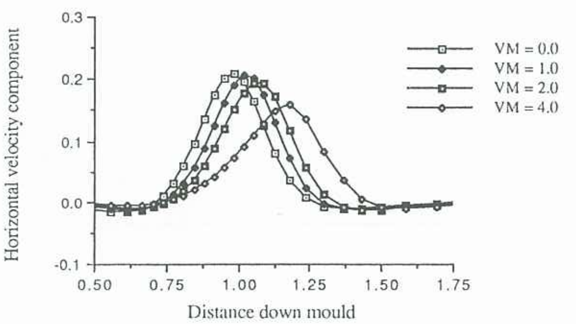


Figure 8. Distributions of the horizontal velocity component down the centre line of the narrow face of the mould.

The effect of inlet vorticity on average and peak surface velocity is shown on figure 8. Both these quantities are reduced as the inlet vorticity is increased. This is due to the inlet fluid jets striking the narrow face lower down the mould,

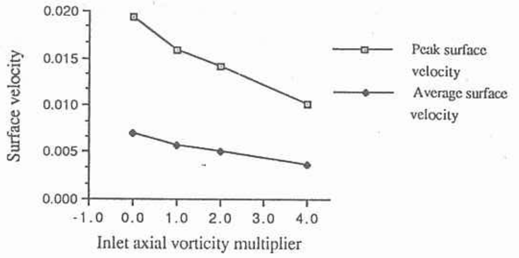


Figure 9. Peak and average surface velocities as a function of inlet vorticity

and with less momentum, providing less driving force for the upper circulating fluid. Reduced surface velocities with increasing inlet axial vorticity will undoubtedly decrease surface disturbance which is usually advantageous for optimum heat transfer to the mould in this region.

CONCLUSIONS

The physical modelling study identified the existence of two counter rotating vortices residing in the bottom of the SEN. The effect of these on the three dimensional flow in the mould has not been studied before. The general flow structure in a continuous casting mould is comprised primarily of two vortices above and below the SEN exit jet. These recirculating zones are in fact part of a more complex three dimensional circulation which stretches around the SEN jet creating a toroid. The main effect of increasing the axial vorticity in the SEN exit jet was to push the SEN exit jet downward, and to decrease the the strength of the jet and surface velocities.

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