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THE APPLICATION OF LDA TO CHARACTERISE CROSS-FLOW FROM AN OSCILLATING JET IN A WATER MODEL OF A THIN SLAB CASTING MOULD

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ABSTRACT

In the metallurgy industry, thin slab continuous casting is commonly used in a number of production processes. Slab casting involves injection of molten metal through a Submerged Entry Nozzle (SEN) into a rectangular mould. At high casting rates characteristic of thin slab casting the SEN jet oscillates which can cause heat transfer and quality control problems. The following work presents Laser Doppler Anemometry (LDA) data from a 1/3 scale water model of the mould which characterises the jet oscillation by measurement of fluid velocity in a cross-flow region around the SEN. The results have shown the cross-flow to be highly transient with an oscillation period dependent on the casting rate of the system. Additional cross-flow which was also observed below the nozzle exit, allowed the jet to oscillate even with zero SEN-mould wall gap width.

INTRODUCTION

Continuous slab casting is now a well established method for producing steel for various applications (Nilles and Etienne, 1991). The technique involves injecting liquid metal into a water-cooled mould as two lateral jets through a Submerged Entry Nozzle (SEN). As the outer edges of the metal cool, they solidify forming a solid shell which increases in thickness as it descends in the mould. The complex nature of the fluid flow in the mould has resulted in significant numerical and physical modelling studies in order to optimise the performance of a given mould geometry. These are reviewed in literature surveys on the use of mathematical and water modelling of conventional continuous casting (Austin, 1992; Herbertson *et al*, 1991).

Recent research has considered thin slab casting aimed at reducing the cost of subsequent hot rolling (Honeyands, 1994). However, the use of a thin mould geometry requires a higher casting speed to achieve the same throughput as a conventional size continuous caster. This results in free surface oscillations of the liquid metal in the mould. These oscillations can cause problems with superheat dissipation and uniformity of shell growth, and can lead to poor product quality (Honeyands *et al*, 1992; Honeyands, 1994). Similar difficulties occur in the strip casting of aluminium (Espedal *et al*, 1993). Understanding the fluid dynamics in the mould is necessary for improved efficiency and quality at increased casting speeds.

Studies with water models of thin slab caster moulds (Honeyands, 1994; Gupta and Lahiri, 1994) show that the observed surface disturbances at increased casting speeds are associated with an unstable flow pattern which causes the jets emanating from the SEN to oscillate across the broad face of the mould. One conclusion (Honeyands, 1994) was that the jet oscillation was similar in nature to that which occurs in a blind cavity (Molloy, 1969). The flow oscillation occurred in the presence of a steady supply to the injection nozzle and was thus not being driven by unsteadiness in the delivery system. One of the workers (Honeyands, 1994) was also able to numerically predict such sustained oscillation in an idealised cavity. More recently, a numerical model has been produced which can predict a single jet oscillation in a two-dimensional mould geometry (Gebert *et al*, 1997). The primary factor limiting further development of computational models of the oscillation is the lack of detailed measurements of the fluctuating flow field.

A feature of the oscillation is a cross-flow through the gap between the nozzle shaft and the broad face of the mould wall. Previous work with a water model (Honeyands, 1994) has found that cross-flow was necessary for the oscillation to occur. In the present paper, cross-flow is investigated using the technique Laser Doppler Anemometry (LDA) (Durst *et al*, 1981). The response of the oscillation to changes in casting rate, nozzle-mould wall gap width and nozzle submergence are presented and a simple relationship between casting rate and oscillation frequency is demonstrated.

EXPERIMENTAL METHOD

Slabcaster Water Model

In order to allow easy optical access for the LDA system a water model was constructed which was based on a glass walled mould. Figure 1 illustrates the overall design of the experimental rig. The mould has dimensions 800mm x 500mm x 180mm although a filler block can also be inserted to vary the mould width from 50-180mm as required. This set-up provided a 1/3 scale model on the broad face for direct comparisons with previous work (Honeyands, 1994). For the work presented here the mould width was fixed to 80mm.

The remainder of the rig consisted of a centrifugal pump supplying a 200 litre tundish mounted 500mm above the mould. The pump was fitted with an overflow to prevent stalling. Water from the tundish was injected into the mould through a glass SEN. The bottom of the glass mould was fitted with a 300mm x 500mm x 100mm outlet chamber and an adjustable slot valve for flow control. This type of manifold was found to give the most reliable jet oscillations and allowed high flow rates. Other designs based on a number of outlet pipes and gate valves were tested but found to give uneven outflows resulting in a biased jet position. With the slot design it was also found that a 250mm x 500mm x 100mm extension was required to prevent air entrainment in the slot outlet area by ensuring the flow outlet level was below the water level of the pump reservoir.

The casting rate of the system was controlled by adjusting the mass flow through the mould. This was done by using a ballcock on the tundish inlet to fix the head and a gate valve on the tundish outlet to tune the SEN mass flow. With this system casting rates of between 0.5 and 2.0 m/min were possible. To monitor the casting rate, a turbine flowmeter was placed 250mm from the pump overflow valve and calibrated.

The SEN simply consisted of a 38mm diameter glass tube with a wall thickness of 2.5mm mounted below gate valve on the tundish. On operating casters, however, a bi-nozzle is generally used. At this stage of the study though, the simpler straight through nozzle was thought more appropriate to investigate the basic characteristics of the oscillating jet and to isolate the most dominant flow features.

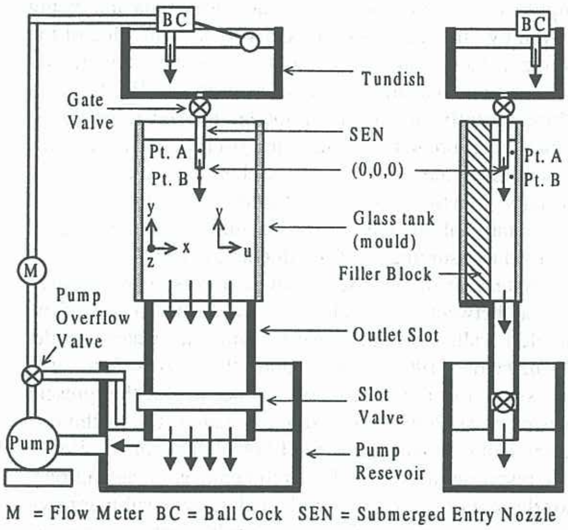

Figure 1 : Schematic diagram of experimental set-up.

LDA System

The LDA measurements were made using a Dantec FibreFlow system and a 58N40 FVA covariance signal processor. A probe focal length of 250mm with *u*, *v* measurement volumes of 0.117mm x 0.117mm x 1.544mm and 0.111mm x 0.111mm x 1.464mm respectively was chosen to ensure sufficient spatial resolution for the expected flow structures. This probe volume also allowed measurement of velocity in the full range of SEN-mould wall gap widths. The fluid was seeded with 10μm metallic coated particles to produce acceptable scattering properties and to adequately follow the fluid flow (Dring, 1982).

Flow Measurements

As shown in work by Honeyands (1994), a cross-flow occurs across the broad face of the mould and allows the jet to oscillate. Therefore LDA measurements were made in this region at points A and B as illustrated in Figure 1. Initially LDA data were recorded for varying SEN submergence and casting rates. These conditions are listed in Table 1.

Work by Gebert *et al* (1994) also suggested the jet oscillation was sensitive to SEN-mould wall gap width. Therefore the SEN width was also varied to change the resistance to cross-flow between the nozzle and mould wall by adjusting the gap between the SEN and mould wall from 0 to 21 mm. This was done by using additional PVC pipes placed over the original glass SEN. Data was sampled at points A and B for 200 seconds at around 100Hz to ensure sufficient temporal resolution for any given oscillation cycle. Point A was positioned at $x = 0$, with y at the midpoint between the free surface and the SEN exit, and in z at the midpoint between the SEN and mould walls. Hence the location of Point A varied, depending on the SEN submergence and SEN-mould wall gap width. Point B was fixed at $x = 0$, $y = 33.0$mm, $z = -29.5$mm and allowed additional cross-flow properties below the SEN to be investigated without being influenced by the SEN jet. This position was determined from y and z LDA traverses adjacent to the jet.

Casting rate (m/min)	SEN submergence (mm)	SEN-mould wall gap width (mm)
2.0	20, 40, 60, 80, 100, 120	21
0.5	120	0, 3, 6, 16, 21
1.0	120	0, 3, 6, 16, 21
1.5	120	0, 3, 6, 16, 21
2.0	120	0, 3, 6, 16

Table 1: Experimental conditions.

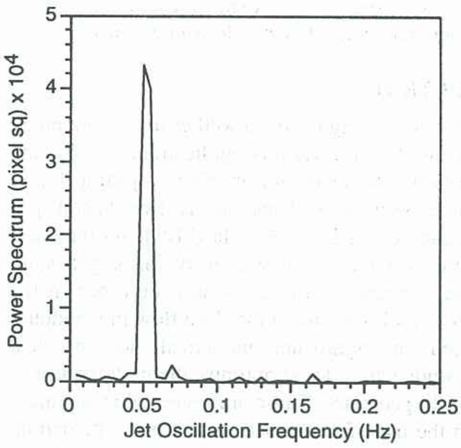

Figure 2 : Power Spectrum at Point A (casting rate 2.0m/min, SEN-Mould gap 21mm).

Data Analysis

Cross-flow characteristics were analysed by processing *u*-velocity data collected from the LDA system into time series, mean and rms velocity where the mean and rms velocities, u_{mean}, u_{rms}, were calculated using a residence time weighting technique (Buchhave *et al*, 1979) to reduce bias effects such that

$$u_{mean} = \frac{\sum_{i=1}^{N_r} u_i \Delta t}{\sum_{i=1}^{N_r} \Delta t} \qquad (1)$$

$$u_{rms} = \frac{\sum_{i=1}^{N_r} \left(u_i - u_{mean}\right)^2 \Delta t}{\sum_{i=1}^{N_r} \Delta t} \qquad (2)$$

and where N_r is the sample size and Δt is the residence time of the particle in the measurement volume.

Each point A and point B time series were processed into a power spectrum to estimate the oscillation period of the jet by using a Fast Fourier Transform (FFT) routine. Before processing, the raw data was resampled into N = 2048 points from the u-velocity over the appropriate time. Figure 2 shows a typical power spectrum. Centroid analysis on the signal peak was used to estimate the dominant frequency.

RESULTS AND DISCUSSION

The cross-flow time series recorded at point A and B were found to be sinusoidal in nature with a relatively stable oscillation frequency. Figure 3 illustrates this result and shows raw LDA data at point A for the u-velocity at a casting rate of 2.0m/min and a SEN-mould gap width of 21.0mm. Over the range of measurement conditions, the cross-flow frequencies varied from between 0.013-0.055 Hz or had corresponding periods of 76.9-18.1s. However, although the cross-flow frequency dominanted the fluid flow, on a shorter temporal scale the flow appeared to be highly transient as shown in the boxed region on the graph. This characteristic was further examined with flow visualisation which showed the flow across the SEN to be unevenly distributed and where reversals of the bulk fluid were happening over sub-second periods. These effects can be attributed to the turbulent nature of two recirculation cells positioned on either side of the main jet in the body of the mould where the Reynolds numbers are in the range $10^4 - 10^5$. The movement of these cells in phase with the jet oscillation has been numerically predicted by Gerbert *et al* (1997) and results in the cross-flow around the SEN. Any unsteadiness in the two cells will therefore result in fluctuations in the cross-flow observed at points A and B.

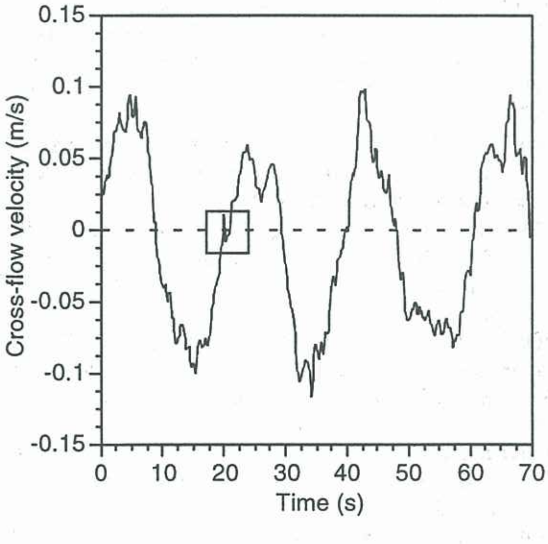

Figure 3 : Point A time series (casting rate = 2.0m/min, SEN-mould gap width = 21.0mm, SEN submergence = 120mm).

The frequency and amplitude characteristics of the cross-flow with changing SEN submergence are summarised in Figure 4. In all of the following, amplitude is plotted in terms of RMS velocity. At points A and B these results show the frequency of cross-flow oscillation to be generally independent of SEN submergence while the cross-flow amplitude decreases with increasing SEN submergence. As discussed previously, the cross-flow occurs because of momentum transfer from jet into the two recirculation cells. Changing the SEN submergence does not significantly affect this entrainment and therefore the oscillation frequency remains almost unchanged and independent of submergence. In contrast, the amplitude will depend on the area available for cross-flow which increases with increasing SEN submergence. Therefore the amplitude will fall with increasing SEN submergence.

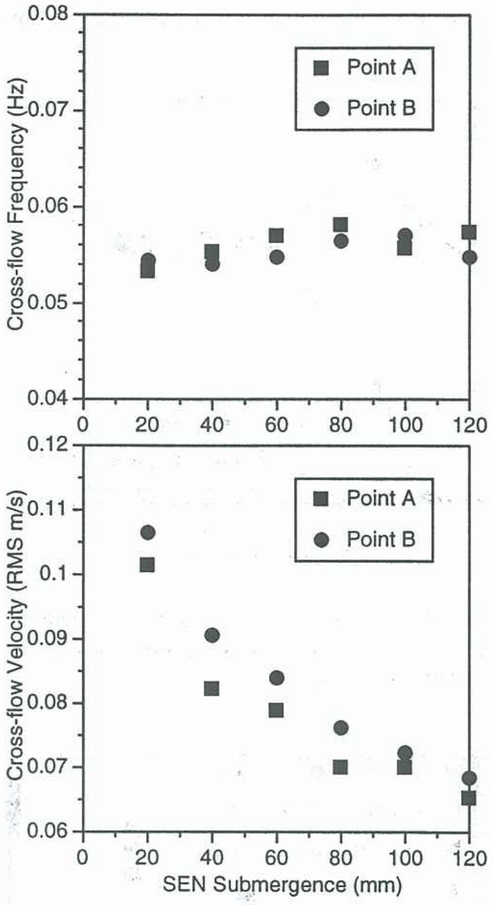

Figure 4 : RMS velocity and frequency of the cross-flow oscillation vs SEN submergence (casting rate = 2.0m/min, SEN-mould gap width = 21.0mm).

The characteristics of cross-flow amplitude with changing SEN-mould wall gap width are plotted in Figure 5. The most significant result to note here is that cross-flow occurs at point B below the SEN exit for any gap width. This cross-flow is possible since the SEN jet requires of number of nozzle diameters in y to expand into the z-width of the mould. This area between the jet boundary and mould wall allows cross-flow at any casting rate or SEN-mould wall gap width and so permits the jet to oscillate even when the gap width has been reduced to zero. Reducing the gap width also increases flow resistance at point A which accounts for the steady reduction in cross-flow amplitude as gap width is reduced to zero. Correspondingly, cross-flow appears to shift to the region below the SEN which results in a increase in amplitude at point B which peaks at a gap width of 6mm.

The characteristics of cross-flow oscillation frequency with changing casting rate are plotted in Figure 6 for a range of SEN-mould wall gap widths. The results clearly show a linear dependence on casting rate. This characteristic is consistent with a constant dimensionless frequency (based on a time scale derived from the casting rate and mould width), such as would occur for a transient flow pattern which is independent of Reynolds number. These results also show the cross-flow oscillation frequency to be generally insensitive to changes in SEN-mould wall gap width (for fixed nozzle inner dianeter) at both point A and point B. This independence of frequency on gap width shows that the instability is determined by the primary confined jet flow in the main body of the mould.

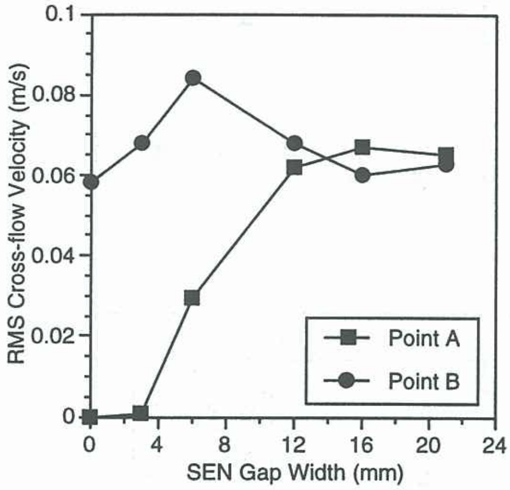

Figure 5 : Characteristics of RMS cross-flow velocity with SEN-mould gap width (casting rate = 2.0m/min, SEN submergence = 120mm).

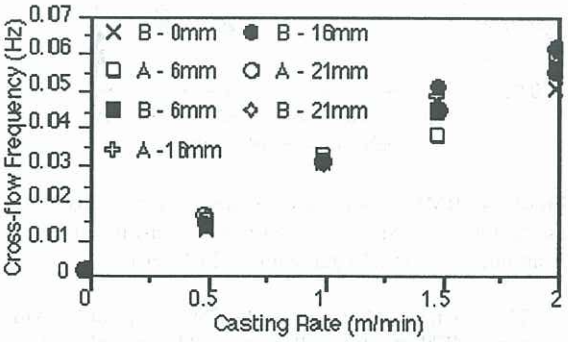

Figure 6 : Characteristics of cross-flow oscillation frequency with casting rate (submergence = 120mm) at points A and B for various gap widths.

CONCLUSION

This paper has described the application of LDA to a 1/3 scale water model of a thin slab continuous casting mould. The oscillatory flow properties in the mould were determined by taking measurements at two points where cross-flow generated from the oscillating jet occurred. This approach has allowed the flow to be characterised with greater detail than in previously published work. The LDA temporal data and flow visualisation showed the cross-flow to be highly transient due to the turbulent nature of the SEN jet. The cross-flow amplitude was found to depend on SEN submergence and SEN-mould wall gap width while the cross-flow oscillation frequency was found to be solely dependent the mould casting rate for fixed mould geometry and SEN internal diameter. Futher cross-flow was also measured in the region below the SEN exit before expansion of the jet across the thin section of the mould. This additional cross-flow permitted the jet oscillation to continue even when the SEN-mould wall gap width was reduced to zero to eliminate cross-flow past the nozzle.

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