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# NUMERICAL PREDICTION OF SUBMERGED OSCILLATING JET FLOW

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## ABSTRACT

Self-sustaining oscillating jet flow of water in a rectangular cavity, having thickness which is small relative to its width, is predicted using a transient two-dimensional numerical model. The model incorporates a resistance coefficient for the cross-flow through the gap between the nozzle and the broad face of the cavity. Cross-flow is necessary for the oscillation to occur. Flow predictions are compared with laser Doppler anemometry (LDA) experimental data for a range of mould widths and fixed nozzle diameter. The frequency of oscillation and the mean flow patterns are shown to be well predicted for an appropriate choice of resistance coefficient.

## NOMENCLATURE

| | |
|---|---|
| $d_i$ | inner nozzle diameter |
| $d_o$ | outer nozzle diameter |
| $f$ | frequency |
| $H$ | cavity thickness |
| $K$ | cross-flow resistance coefficient |
| $L$ | distance from the free surface to the flow exit |
| $Q$ | volumetric flow rate |
| $R$ | casting speed |
| $S$ | submergence depth of the nozzle |
| $St_d$ | Strouhal number |
| $\mathbf{u}$ | velocity vector |
| $U_c$ | cross-flow velocity |
| $U_{cp}$ | predicted cross-flow velocity |
| $V_{in}$ | mean velocity at the nozzle tip |
| $W$ | width of the cavity across the broad face |
| $x$ | horizontal coordinate across the broad face |
| $y$ | upwards vertical coordinate |
| $z$ | transverse coordinate |
| $\rho$ | fluid density |

## INTRODUCTION

In continuous casting of steel, the liquid metal is injected into a water-cooled mould as two lateral jets through a submerged entry nozzle (SEN). The complex nature of the flow and its effect on heat transfer and solidification has resulted in significant numerical and physical modelling studies. These range from the implementation of combined models (e.g. Huang et al., 1992; Seyedein and Hasan, 1997) to those directed at flow specific aspects (e.g. Thomas et al., 1990; Najjar et al., 1995). Austin (1992) has reviewed the literature on the modelling of conventional continuous casting and Herbertson et al (1991) have reviewed the use of mathematical and water modelling. More recently, Samarasekera et al. (1997) reviewed the modelling of both past and new developments in the technology.

One new development is that of thin slab casting. The higher casting speeds required to achieve the same material throughput as a conventional continuous caster can result in free surface oscillations of the liquid metal in the mould. Such oscillations can adversely affect superheat dissipation, uniformity of the solidifying shell, and can lead to poor product quality. Understanding the transient fluid flow in the mould is necessary for improved performance at increased casting speeds.

Simple image analysis, free surface measurements and flow visualisation in water models of thin slab caster moulds (Gupta and Lahiri, 1994; Honeyands, 1994, Honeyands and Herbertson, 1995) indicate that the observed surface disturbances are associated with a self-sustaining oscillation of the jets exiting (at constant flow rate) from the SEN. Recently, the authors have completed an extensive experimental program to measure the oscillating flow field and the turbulence characteristics in a water model of a thin slab caster mould, using the Laser Doppler Anemometry (LDA) and Particle Image Velocimetry (PIV) techniques. Initially flows with an idealised nozzle consisting of a simple pipe (straight-through SEN) was considered (Lawson and Davidson, 1998a,b, 1999a). The data for twin lateral jets from a bi-nozzle characteristic of industrial practice is presently undergoing analysis.

Computational modelling of self-sustained flow oscillations relevant to continuous casting was initiated by Honeyands (1994) who calculated such an oscillation of a single jet entering a blind cavity with free outflow conditions at the top, as observed by Molloy (1969). A more appropriate system was considered by Gebert et al. (1998a,b) who numerically predicted single jet oscillation from a straight-through SEN using a two-dimensional model with outflow at the bottom of the mould. However, they made no quantitative comparisons with experimental data. The aim of the present paper is to provide such comparisons with some velocity data previously obtained for a water model by Lawson and Davidson.. The predicted oscillation frequency and mean flow velocity profiles in the jet will be compared with the measured values for a range of mould widths and fixed nozzle diameter of a straight-through SEN. A more comprehensive comparison with flow data will be reported elsewhere (Lawson and Davidson, 1999b). The extension to 3-D including the bi-nozzle case will be the subject of subsequent papers.

## MODEL DESCRIPTION

Gebert et al. (1998a,b) developed a transient two-dimensional computational flow model of submerged injection from a straight-through SEN into a thin rectangular cavity. Outflow occurs at the bottom of the cavity. The model successfully predicted sustained oscillations of the jet when the flow rate was steady. Figure 1 shows a schematic of the model flow geometry. For the experiments simulated in this paper, $L$ = 1050 mm (length of the cavity), $d_i$ = 33mm (SEN diameter), and $S$ = 120mm (depth to which the SEN tip is submerged). The mould width $W$ is in the range 100 - 500mm.

An oscillating cross-flow between the nozzle shaft and the broad face of the cavity wall is associated with the oscillation of the jet. This is shown schematically in Figure 1. In practice, additional cross-flow can occur between the jet and the cavity wall below the SEN exit (Lawson and Davidson, 1998a,b). If cross-flow is physically prevented then jet oscillation will not occur. Indeed the essential feature of the Gebert numerical model, which permits the prediction of jet oscillation, is that it includes a representation of the cross-flow. This is achieved in the two-dimensional model by representing the inlet flow as an internal mass source while allowing flow to occur past the region occupied by the nozzle. However, any additional cross-flow past the jet is not modelled.

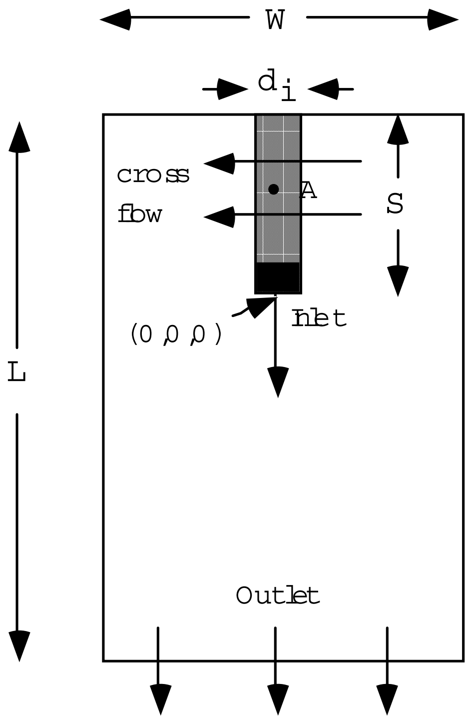


**Figure 1**: Schematic of the flow geometry used by the numerical model. The black square defines the inlet and the grey area represents the region of the SEN in which a resistance to cross-flow is set. The length ($L$ = 1050 mm) extends from the liquid surface to the slot valve through which the fluid exits in the experimental rig.

.In Figure 1 the inlet is defined as the lower face of the small (black) rectangular region near the nozzle tip which is removed from the computational domain. The top and side faces of this tip region are taken to be no-slip boundaries. A velocity profile consistent with the 1/7$^{th}$ power law for fully developed turbulent pipe flow is chosen at the inlet. The remainder of the region occupied by the nozzle (the grey region in Figure 1) is retained in the computational domain and is available for cross-flow. The SEN obstructs the cross-flow, and the effect of this is modelled by a resisting force of the form $K|\mathbf{u}|\mathbf{u}$ in the momentum equation, where $K$ is a constant. The resistance coefficient $K$ is taken to be zero everywhere except in the SEN region (grey area in Figure 1). The model geometry takes no account of the nozzle wall thickness, although this could be implemented if required.

The top boundary of the computational domain represents the free surface which is taken to be a stationary, horizontal, free-slip boundary. No-slip conditions together with standard wall functions are applied at solid boundaries. Turbulence is represented by the standard $k$-$\varepsilon$ model. Outflow at the bottom boundary is determined by a mass flow condition in which zero normal gradients are applied.

The fluid flow computer program CFX4 (AEA Technology, 1997) is used to calculate the model flow using finite volume methods. The solution is based on the SIMPLEC algorithm for the pressure correction. Advection of the turbulence variables $k$ and $\varepsilon$ is calculated using the van Leer scheme. For all other transported variables, advection is based on the QUICK scheme. Numerical details relating to the mesh density, differencing schemes, and tests for numerical accuracy are given by Gebert et al. (1998a). They estimated that time step and mesh density errors in the calculated velocity were less than 10%.

## RESULTS AND DISCUSSION

### Cross-flow Oscillation

Gebert et al (1998a,b) demonstrated and discussed the cyclic behaviour of the predicted jet flow and the associated cross-flow for test cases, but without the benefit of corresponding experimental data. For the water experiments simulated here using the Gebert model, Figure 2 compares the measured and predicted frequency and peak velocity of cross-flow as a function of mould width $W$ for varying mould thickness $H$. The frequency results are plotted in terms of a Strouhal number ($St_d$) based on nozzle internal diameter ($d_i$) and mean inlet velocity ($V_{in}$). The peak velocity results are scaled by $V_{in.}$ The width $W$ is scaled by the length ($L$ = 1050mm) of the model flow domain which is the distance from the free surface to the outflow boundary. A value of dimensionless resistance coefficient $Kd_i/\rho$ = 0.594 (based on $\rho$ = 1000 kg/m$^3$) was chosen in the numerical model to give the "best" prediction for frequency in the base case ($W$ = 500mm and $H$ = 80mm).

The comparisons shown in Figure 2 are taken at a point (A) in the cross-flow region. Point A lies on the centre-line of the broad face of the mound, vertically midway between the free surface and the SEN tip, and transversely midway between the SEN and the mould wall. In terms of the 2-D flow model, point A is represented as shown in Figure 1.

The measured frequency of the cross-flow oscillation is independent of the three mould thicknesses considered ($H$ = 55, 80,105 mm). The predicted dimensionless frequency ($St_d$) compares well with the measured values. Like the experimental results for $H$ = 80, 105 mm, no oscillation was predicted when $W/L$ = 0.1. It likely that the agreement between the predicted and experimental values can be improved in the lower range of $W$ by adjusting the value chosen for $Kd_i/\rho$; however, this seems of little value since measurement errors for $St_d$ are estimated to be approximately 8 - 14%.

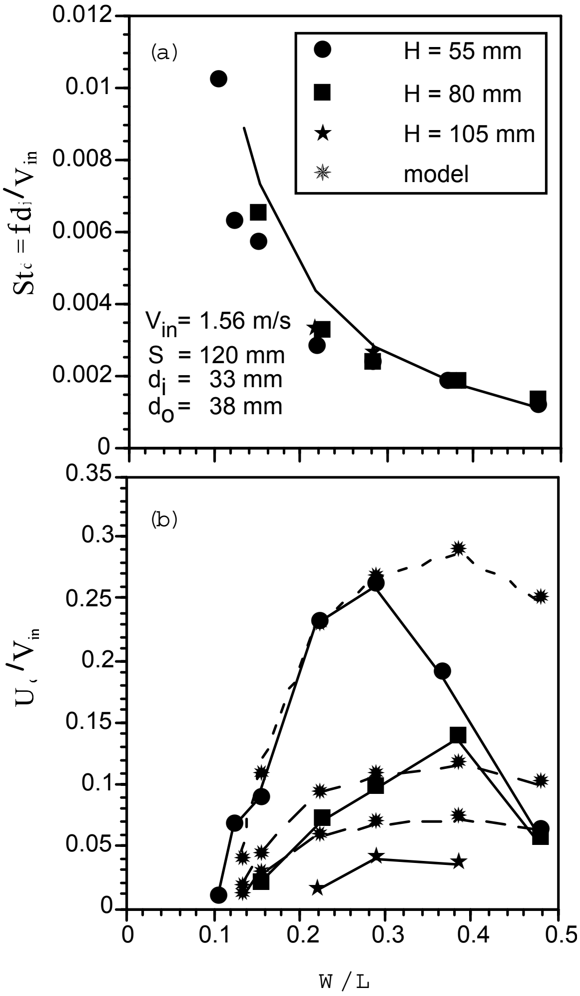


**Figure 2**: (a) Predicted and measured variation at point A of cross-flow oscillation dimensionless frequency (expressed as a Strouhal number based on nozzle diameter), and (b) dimensionless peak cross-flow velocity with width $W$ of the mould for different mould thicknesses $H$. Velocities are scaled by the average velocity $V_{in}$ at the SEN exit. The solid line in (a) and dashed lines in (b) show predictions derived from the two-dimensional model.

Although the mould thickness $H$ is not used in the flow calculation of the two-dimensional model, the value of $H$ is required to estimate a cross-flow velocity which can be compared with the value $U_c$ measured in the gap ($H$-$d_o$) between the nozzle and the mould wall at point A. The theoretical cross-flow velocity is taken to be

$$U_{cp} = \frac{U_{calc}}{V_{in}} \frac{Q}{Hd_i} \frac{H}{H-d_o} \qquad (1)$$

where $U_{calc}$ is the horizontal velocity calculated at point A in the two-dimensional model, and $Q$ denotes the volumetric flow rate through the nozzle and entering the mould. Multiplying $U_{calc}/V_{in}$ by $Q/Hd_i$ gives the velocity which would be obtained by assuming that the mould geometry is uniform in the transverse direction (which it clearly is not because of the SEN) with the two-dimensional model representing any planar section parallel to the broad face. The multiple $H/(H- d_o)$ accounts for the gap width $(H- d_o)$ actually available for cross-flow compared with the mould thickness $H$.

Figure 2b compares the predicted ($U_{cp}$) and experimental ($U_c$) peak cross-flow velocities at Point A, normalised by the experimental inlet velocity, as a function of $W$ for the $H$ = 55, 80, 105mm. The comparisons are reasonable considering the inability of a two-dimensional model to predict the detailed out-of-plane velocity profile past the nozzle.

The cross-flow velocities in Figure 2 exhibit maxima, with the lowest values occurring at the largest and smallest values of $W/L$ in each case. No data are shown for $W/L$ < 0.2 and $W/L$ > 0.4 when $H$ = 105mm, as no oscillation occurred in those cases. The maxima in the cross-flow velocities for varying mould width $W$ occur because the oscillation should cease when W has limiting small or large values. The smallest mould width theoretically possible is $W = d_o$. In that case, no cross-flow is physically possible, and no oscillation will occur. At the other extreme, if the side walls are removed ($W \rightarrow \infty$), the flow is similar to a free two-dimensional jet, in which case cross-flow should again be zero.

### Jet Flow

In Figures 3 and 4, the horizontal, upward vertical, and transverse co-ordinates are denoted by $x$, $y$, $z$, respectively, with an origin located at the centre of the circular opening at the SEN tip.

Figure 3a compares measured and predicted radial profiles of the mean downwards dimensionless velocity in the jet just below the nozzle tip ($y$ = -32mm) for different nozzle diameters and a fixed flow rate. The model prediction is based in a SEN diameter of 33mm. The experimental velocity profiles are insensitive to the nozzle diameter since the dimensionless inlet velocity should be the same in all cases (the flow pattern away from solid walls is independent of Reynolds number in turbulent flow). The close agreement achieved by the corresponding model prediction verifies the validity of the 1/7$^{th}$ power law velocity profile (corresponding to fully developed turbulent pipe flow) chosen at the model inlet.

Experimental and predicted mean centre-line velocities are compared in Figure 3b. Again the dimensionless velocity variation is not sensitive to the choice of nozzle diameter. Agreement with the experimental values is satisfactory with the model under-predicting the centre-line velocity slightly at intermediate values of $y/d_i$ .If the model flow field is constrained to be steady and symmetric about the vertical axis, the predicted velocity on the centre-line (dashed line) is too large. This occurs because of reduced lateral momentum transfer in the absence of an oscillation.

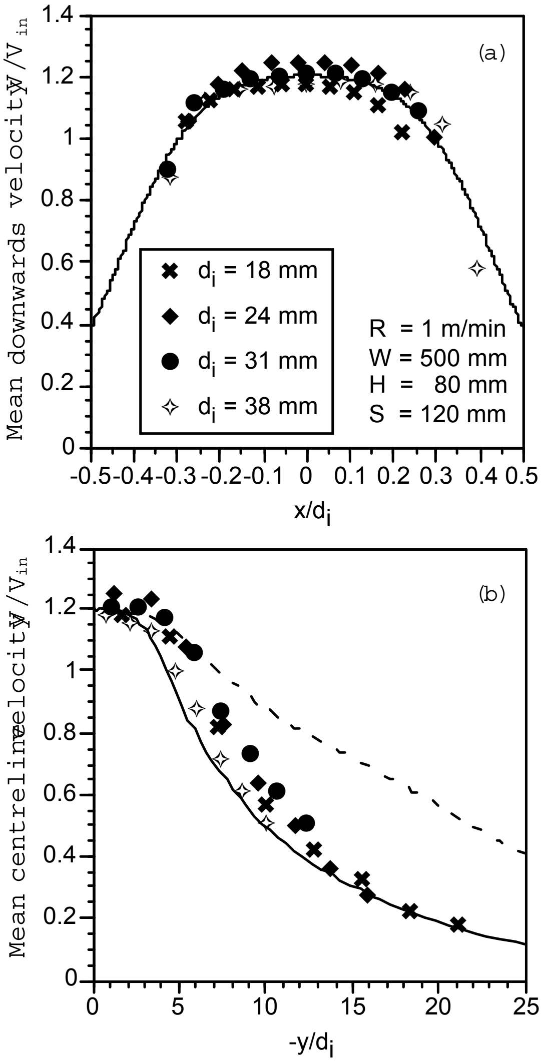


**Figure 3**: (a) Horizontal profile of mean downwards jet velocity at $y$ = -32 mm, $z$ = 0 below the nozzle exit, and (b) mean downwards centre-line velocity of the jet. Velocities are scaled by the corresponding average velocity $V_{in}$ at the SEN exit. The solid lines show the scaled values predicted by the 2-D model for $d_i$ = 33mm with $Kd_i/\rho$ = 0.594. The dashed line corresponds to predictions from a flow model which is constrained to be steady and symmetric.

Figure 4 compares dimensionless predicted and experimental horizontal profiles of the downwards velocity at selected distances below the nozzle tip. The transient numerical model prediction agrees well with the corresponding experimental profiles. There is a slight over-prediction with increasing distance away from the centre, and an under-prediction at the centre-line consistent with Figure 3b. An over-prediction of the peak occurs at the centre with the steady numerical model because it does not account for momentum dispersion by the oscillation; this is also consistent with Figure 3b. This over-prediction is least nearer the nozzle tip because the oscillation is smaller there (right at the nozzle tip there is no oscillation as the in-flow is steady). Note that the steady model actually gives a better prediction of the mean velocity away from the centre-line than the transient model does (the reason for this is not known). However, the transient model gives a better overall prediction.

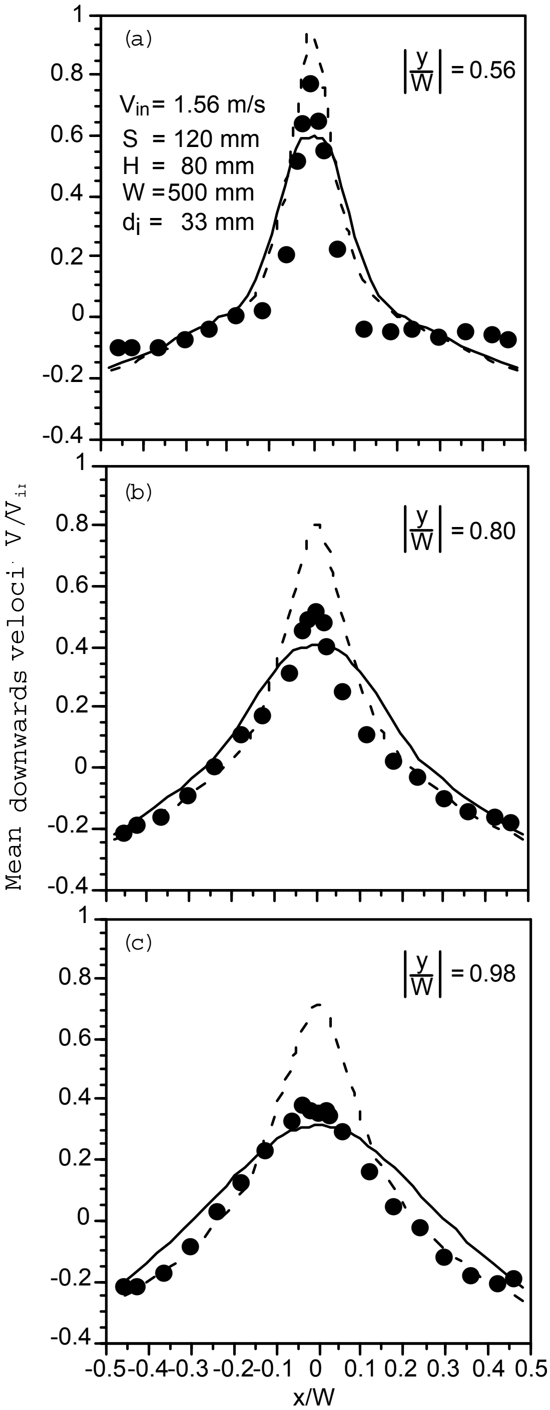


**Figure 4**: Horizontal profiles of the mean downwards jet velocity at different locations downstream of the nozzle tip in the vertical plane $z$ = 0.. Velocities are scaled by the average velocity $V_{in}$ at the SEN exit. The solid lines show the values predicted by the two-dimensional model with $Kd_i/\rho$ = 0.594. The dashed line corresponds to predictions from a flow model which is constrained to be steady and symmetric.

## CONCLUSION

Recent flow experiments conducted by the authors using a water model of submerged injection from an idealised straight-through nozzle into a thin slab casting mould are simulated with a 2-D transient numerical model. The jet emanating from the nozzle oscillates even though the flow rate is steady. A cross-flow between the nozzle and the broad face of the cavity wall occurs in close association with the jet oscillation.

The dimensionless frequency (Strouhal number) of the cross-flow oscillation is well predicted for varying mould widths assuming a particular choice of cross-flow dimensionless resistance coefficient. The measured peak cross-flow velocity is less well predicted but is considered acceptable since the 2-D numerical model cannot predict the out-of-plane cross-flow velocity profile past the nozzle.

The dimensionless mean velocity profiles along the centre-line, and horizontally at different vertical locations in the jet, are well predicted. For comparison, corresponding predictions by a steady numerical model which is constrained to be symmetric are also presented. The steady model substantially over-predicts the peak in the jet mean velocity profile because it does not account for momentum dispersion by the oscillation. However, away from the centre-line the steady model predicts the mean velocity profile for closely than the transient model.

Although the phenomenon of self-excited jet oscillation is of generic interest, the motivation of the theoretical and experimental study of such behaviour by the authors (of which the present work forms a part) is its relevance to fluid flows in thin slab casting. Since a bi-nozzle rather than a straight-through nozzle is typical of industrial practice, the main value in studying the jet oscillation from a straight-through nozzle is that it is a simpler flow with a similar oscillation mechanism. Experience in modelling this simpler system will guide the numerical calculation of the more realistic case. Experimental measurements of transient bi-nozzle flow by the authors (to be presented elsewhere) show that the oscillation of this flow is indeed more complex than that for the straight-through nozzle, as is expected. The bi-nozzle flow oscillations observed by the authors are spread over a range of frequencies with no single dominant value. Numerical modelling of the 3D flow from a bi-nozzle is currently underway.

## ACKNOWLEDGEMENT

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## REFERENCES

AEA Technology, (1997), *CFX-4.2 Solver Manual*, AEA Technology, Harwell Laboratory, Oxfordshire, UK.

AUSTIN, P.R., (1992), "Literature survey on modelling of continuous casting" *BHP unrestricted Report*, Report No. BHPR/PMR/R/92/044, Dec.

GEBERT, B.M., DAVIDSON, M.R. AND RUDMAN, M.J., (1998a), "Computed oscillations of a confined submerged liquid jet", *Applied Mathematical Modelling*, **22**, 843 – 850.

GEBERT, B.M., DAVIDSON, M.R., AND RUDMAN, M.J., (1998b), "Calculation of an oscillating liquid jet in a two-dimensional cavity", *Computational Techniques and Applications: CTAC-97,* (Eds. J. Noye, M. Teubner, and A. Gill), World Scientific, 217 – 224.

GUPTA, D. and LAHIRI, A.K., (1994), "Water modelling study of the surface disturbances in continuous slab caster", *Metall. Mat. Trans B*, **25B**, 227 – 233.

HERBERTSON, J., HE, Q.L., FLINT, P.J. and MAHAPATRA, R.B., (1991), "Modelling of metal delivery to continuous casting moulds", Iron and Steel Society Vol. 74, *1991 Steelmaking Conf. Proc.*, Washington DC, April, 171-185.

HONEYANDS, T.A., (1994), *Flow Dynamics in Thin Slab Caster Moulds*, PhD Thesis, University of Newcastle, Australia.

HONEYANDS, T.A. and HERBERTSON, J., (1995), "Flow dynamics in thin slab caster moulds", *Steel Research*, **66**(7), 287 - 293.

HUANG, X., THOMAS, B.G. and NAJJAR, F.M. , (1992), "Modelling superheat removal during continuous casting of steel slabs", *Metall. Trans. B*, **23B**, 339-356.

LAWSON, N.J. and DAVIDSON, M.R., (1998a), "Measurement of cross-flow characteristics from a transient water model of a thin slab casting mould" *IMechE Optical Methods and Data Processing in Heat and Fluid Flow*, London, 16-17 April 1998 (Eds: Bryanston-Cross et al), 301 - 310.

LAWSON N.J. and DAVIDSON M.R., (1998b), "The application of LDA to characterise cross-flow from an oscillating jet in a thin slab casting mould" *13th Australasian Fluid Mechanics Conference*, 13 - 18 December 1998, Monash University, Melbourne, Australia., (Eds: Thompson M.C., Hourigan K.), 667-670.

LAWSON N.J. and DAVIDSON M.R., (1999a), "Cross-flow characteristics of an oscillating jet in a thin slab casting mould", accepted for publication in *J. Fluids Eng.*

LAWSON N.J. and DAVIDSON M.R., (1999b), "Self-sustained oscillation of a submerged jet in a thin rectangular cavity", in preparation for *J. Fluids and Structures*.

MOLLOY, N.A., (1969), "Oscillatory flow of a jet into a blind cavity", *Nature*, **224**, 1192 – 1194

NAJJAR, F.M., THOMAS, B.G. and HERSHEY, D.E., (1995), "Numerical study of steady turbulent flow through bifurcated nozzles in continuous casting". *Metall. and Mat. Trans B*, **26B**, 749-764.

SAMARASEKERA, I.V., THOMAS, B.G. and BRIMACOMBE, J.K., (1997), "The frontiers of continuous casting", *Proc. of The Julian Szekely Memorial Symposium on Materials Processing*, Cambridge, Massachusetts, October 5-8, (Eds. H.Y. Sohn, J.W. Evans and D. Apelian), The Minerals Metals and Materials Soc., 275-297.

SEYEDEIN, S.H. and HASAN, M., (1997), "A three-dimensional simulation of coupled turbulent flow and macroscopic solidification heat transfer for continuous slab casters", *Int. J. Heat Mass Transfer*, **40**(18), 4405-4423.

THOMAS, B.G., MIKA, L.J. and NAJJAR, F.M., (1990), "Simulation of fluid flow inside a continuous slab-casting machine", *Metall. Trans. B*, **21B**, 387-400.