1. Introduction

The direct casting of alloys into strips approximately 5 mm thick for the production of coils and sheets simplifies the conventional route that involves hot rolling 150 to 250 mm thick slabs into final dimensions. The technology required to cast strips is however entirely different from the one used to produce slabs. Advances in this field have shown that using two counter-rotating rolls of equal diameter is probably the most efficient method to produce strip. Interestingly this configuration is the one proposed by Bessemer more than a century ago.

For sheet metal applications, the requirements of the as-cast surface quality of strips are high and optimizing the fluid flow in the mold of the caster is crucial to this achievement. Factors not related to fluid flow also affect the surface quality, for example, heat transfer at the roll-strip interface and camber of the rolls but will not be addressed in this paper. Two important flow conditions that must be met are quiescence at the pool surface and high regeneration rate of fluid near the surface. Quiescence must be maintained to provide a stable meniscus. This leads to a uniform contact time of the strip across the entire roll width which is necessary to produce even solidification. A high regeneration rate at the top of the pool is also required even though forced convection in the pool produces low temperature gradients in the bulk liquid because zones of solidified metal—skulls—may form at the surface. These may be a serious source of perturbation in the process leading to numerous defects in the strip. In addition, the fluid exiting the nozzle possesses sufficient superheat to locally remelt the mushy zone of the strip. Thus, if the flow is directed deep into the pool rather than towards the top, it may then promote uneven solidification by remelting some solidified alloy. The presence of quiescence and high regeneration rate of the top of the pool that is simultaneously required is particularly difficult to obtain due to the shallowness and exiguity of the mold.

Pool quiescence and fluid regeneration rate are directly affected by metal delivery from the tundish. The system used to feed the pool, normally consisting in a submerged entry nozzle, is thus a key component of this process. In the water modeling study presented in this paper, various nozzle configurations were evaluated in terms of agitation at the pool surface and fluid regeneration. Agitation at the pool surface was evaluated by measuring level fluctuations with an ultrasonic detector. A similar procedure has also been cited in other reports. The evaluation of the regeneration rate of fluid in the vicinity of the pool surface was determined from residence time distribution, RTD, measurements. The technique is common to optimize flow in tundishes but it is here shown that it may be used to diagnose nozzles in the mold of a strip caster. In tundishes, the measurements are normally carried out at the outlet and the overall or global behavior is characterized. In this work, the measurements were local and restricted to the top portion of the pool, i.e., a depth of 30 to 40 mm below the surface. A short residence time of the fluid in that region indicates the presence of a high replacement rate by the desired one from the delivery system. An ideal delivery system should thus produce minimal agitation at the pool surface and maximal regeneration rate of fluid in that vicinity. The performance of various nozzle geometries was thus evaluated with these two criteria and the effects of process param-
ters such as nozzle immersion depth, pool volume and flowrate were examined.

The liquid alloy that was simulated with water was one of copper. Steels such as stainless,12,13) carbon,14,15) iron-silicon16) as well as alloys of nickel17) and aluminum18) have already been cast by the twin roll process but those of copper have not been subjected to much experimentation. A research program to evaluate their castability has been undertaken at the Industrial Materials Institute and this study was carried out to identify a suitable nozzle and the effect of key process features related to fluid flow. The methodology described in this paper is general and can be applied to other alloys and continuous casting processes where the distribution of fluid in the upper portion of the mold is also a concern.19,20)

2. Theory—Similarity Aspects between Model and Prototype

The flow conditions that were desired to be reproduced were turbulence, flow patterns and wave motion. The forces responsible for these phenomena are inertia, viscosity, gravitation and surface tension.6) Consideration was thus given to following dimensionless groups:

\[
\text{We} = \frac{\rho U^2 L}{\sigma} \quad \text{inertia force} \quad \text{surface tension force} \quad \text{(1)}
\]

\[
\text{Re} = \frac{\rho UL}{\mu} \quad \text{inertia force} \quad \text{viscous force} \quad \text{(2)}
\]

\[
\text{Fr} = \frac{U^2}{gL} \quad \text{inertia force} \quad \text{gravity force} \quad \text{(3)}
\]

To obtain a dynamic similarity between the model and the prototype, these force ratios must be the same in both systems. Considering the thermophysical data of water and liquid copper listed in Table 1, the scale factor, \( \lambda \), defined as

\[
\lambda = \frac{L_m}{L_p}
\]

and the average fluid velocity at the exit of a circular port nozzle given as

\[
U = \frac{4Q}{\pi D^2}
\]

the relationship between the scale factor and flowrates for a Weber based model is then: \( \lambda^{5/2} = 1.5Q_m/Q_p \) and for Reynolds: \( \lambda^{5/2} = 4Q_m/Q_p \).

The physical properties of water and liquid copper are such that only two of these three relationships can be simultaneously satisfied. For example, a Froude–Reynolds model is obtained when \( \lambda = 1.37 \) and \( Q_m/Q_p = 2.20 \), whereas a Weber–Froude model requires \( \lambda = 0.67 \) and \( Q_m/Q_p = 0.37 \).

In the present study, the model used was at full scale with the prototype. It had previously been constructed to study liquid steel flow21) and this scaling provides a simultaneous similitude with Froude and Reynolds numbers.59) A scaling factor of unity to model the behavior of liquid copper imposes the selection of one dimensionless grouping rather than two. The predominant one was chosen by considering typical casting conditions in the prototype, i.e., liquid copper feeding the mold at a flowrate of \( 3 \times 10^{-4} \text{m}^3/\text{s} \) using a bifurcated nozzle with two ports, each 18 mm in diameter. Under these conditions, the average fluid velocity at the exit of a port, given by Eq. (5), is \( 0.6 \text{m/s} \). Taking the port diameter, 18 mm, as representing the characteristic length, \( L \), and the thermophysical properties of liquid copper listed in Table 1, values for the Weber, Reynolds and Froude numbers are approximately \( 40, 2 \times 10^4 \), and 2, respectively. This indicates that preference should be given to a Froude based model since the two predominant forces are those of inertia and gravity. Although modeling of liquid metal in continuous casting molds is more frequently carried out using two criteria, Froude–Reynolds20,22–24) or Weber–Froude,25–27) a single criterion, Reynolds59,29) or Froude26–32) has also been utilized. Modeling of flow in tundishes is also commonly based on the Froude number alone.31)

With a scaling factor of unity, the similitude of the Froude number between the model and the prototype implies that the flowrate of water must be the same as that of copper. Using the same typical casting conditions given previously, the Reynolds number in the model is then approximately \( 1 \times 10^4 \) compared to \( 2 \times 10^4 \) in the prototype. This difference has small consequences on the bulk flow since the viscous force is negligible in both cases, turbulent regimes being well established. The Weber number in the model is approximately 100 compared to 40 in the prototype. Although the model underestimates surface tension, this should have small repercussions on the macroscopic motion of the surface which is more strongly affected by gravity waves than capillary waves.23)

Table 1. Selected thermophysical properties of water and pure liquid copper.

| Property          | Water (20°C) | Ref. | Liquid Copper (1085°C) | Ref. |
|-------------------|--------------|------|------------------------|------|
| Viscosity (Pa s)  | 1.0 \times 10^{-3} | 34   | 4.34 \times 10^{-3} | 35   |
| Density (kg/m³)   | 998          | 34   | 8090                   | 35   |
| Surface tension (N/m) | 7.3 \times 10^{-2} | 34   | 1.3                    | 35   |

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Fig. 1. Schematic depiction of the water model.
3. Set-up and Procedure

The water model is depicted in Fig. 1 and was identical to one used in a previous study. The pool was contained in the cavity between the two aluminum rolls and the Plexiglas side dams. The rolls were 0.203 m in width and 0.610 m in diameter, the same dimensions as the prototype used at the Industrial Materials Institute. They were driven by two 1.5 kW motors. The rotation velocity of the rolls was controlled via a potentiometer and the gap between them was fixed at 5 mm. The inflow of water in the pool was controlled by the stopper rod located in the tandish. It was coupled to an actuator which moved the rod to open or close the outlet orifice in the tandish according to the water level readings in the pool measured by the ultrasonic detector. This sensor was positioned 300 mm above the water level and 50 mm away from one of the two rolls. It monitored fluctuations of the pool level at a data acquisition rate of 30 Hz. The agitation at the pool surface produced by the flow of water exiting a nozzle at a given immersion depth and pool height was defined as two standard deviations of the average in the level measurements taken for a period of 120 s. Immersion depth was defined as the distance between the center of the port nozzle and the pool surface. Pool height was from the free surface to the minimum distance between the rolls. A valve beneath the rolls controlled the outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total outflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total inflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total inflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total inflow of water from the pool and the flowrate was measured with a rotameter. Although water leakage from the side dams accounted for less than 5% of the total inflow of water from the pool and the flowrate was measured with a rotameter.

4. Results and Discussion

The flow patterns of nozzles having their jets oriented towards the side dams, nozzles No. 1 to 5 in Table 2, were observed to have similar features and are depicted in Fig. 3(a). They are the same as those identified in an earlier study. In the case of nozzles No. 1 to 4, approximately half of the dye cloud bifurcated upward after colliding against the side dam, the other half going downward. For nozzle No. 5, the dye exited the orifice of the nozzle with an initial downward angle before colliding the side dam. Approximately one quarter bifurcated upward, the rest heading downward. As shown in Fig. 3(b), the flow pattern of the nozzle with its jets directed towards the rolls, nozzle No. 6, was mainly the same along the entire width of the rolls. Approximately three quarters of the dye cloud rose to the upper portion of the pool after impinging the rolls. The curvature of the roll appeared to contribute to this preferential upward deflection. The main difference between the flow patterns of the two types of nozzles is that the first are tri-dimensional and the second are bi-dimensional. They are in fair agreement with those obtained by numerical modeling of fluid flow in a twin roll caster. In Fig. 4, pool level variations produced by the two types of nozzles are shown as a function of time. Significantly more fluctuations are produced with

Table 2. Nozzle characteristics.

| Nozzle | Port diameter (mm) | Port angle | Sump depth (mm) |
|--------|--------------------|------------|-----------------|
| 1      | 11                 | 0°         | 0               |
| 2      | 18                 | 0°         | 0               |
| 3      | 22                 | 0°         | 0               |
| 4      | 18                 | 0°         | 22              |
| 5      | 18                 | 25° (down) | 0               |
| 6      | 10x50              | 0°         | 0               |

*Shaft diameter of all nozzles is 63 mm.
*Port angle is given with respect to water level.
the nozzle with its ports oriented towards the side dams. The small port surface area of this nozzle and its flow patterns are two factors that account for this greater agitation. From Eq. (5), it is seen that for a given flowrate, the velocity of the fluid exiting the nozzle is inversely proportional to the surface area of the port nozzle. It is important to emphasize that these measurements were obtained under steady state conditions. These were established approximately 1 min after the start up during which the pool was filled. Experiments with liquid metal using the twin roll caster at the Industrial Materials Institute, also normally require this time to stabilize the conditions and the process is highly perturbed during this period.

The fluctuations depicted in Fig. 4 are relatively small compared to those reported in a thin slab water model where they reached 20 to 30 mm. As will be seen later, the bulk of the fluctuations of the present study were smaller than 3.5 mm. Preliminary tests had shown that at this magnitude, the results were not strongly affected by the position of the detector and the measurements gave a fairly good representation of the overall pool behavior. This was considered to be mainly caused by the small volume of the pool (~2·10⁻³ m³). It would nevertheless have been preferable to measure the fluctuations directly at the meniscus, where the fluid contacts the rolls, since defects in cast strips often originate there. Direct measurements at this location have been conducted before on the water model of a twin roll caster. An assumption therefore made in this work is that reducing level fluctuations at the free surface of the pool will also reduce them at the meniscus.

The effect of immersion depth on level fluctuations of the nozzles listed in Table 2 is shown in Fig. 5. The presence of maximums in some of the curves can be observed. The reason is not clear but this may be caused by the upward deflection of the fluid from the arc of the rolls mentioned earlier. Aside from nozzle No. 1, there is no substantial gain in pool surface quiescence that can be obtained by increasing the immersion depth of nozzles. This is mainly explained by the limited range of immersion depths investigated (30 mm) that was imposed by the shallowness of the mold of this process. It is noted that increasing the port diameter from 11 to 18 mm, nozzles No. 1 and 2, is beneficial to reduce level fluctuations as predicted by Eq. (5) but a further increase to 22 mm, nozzle No. 3, does not yield as large an improvement. Comparison of results for nozzles No. 2 and 4 indicates that the sump has virtually no quieting effect. This is in agreement with a mathematical modeling study but in disagreement with one performed with a physical model. In the latter case, the increased surface pool quiescence was however based only on a visual examination. The use of a sump has been cited to be beneficial when a large pressure drop variation occurs across the port diameter, the top portion being at a lower pressure than the bottom. In some instances this pressure difference is claimed to be sufficient to produce stagnation or even flowback of the fluid into the nozzle and a sump is considered to produce a greater pressure drop uniformity across the entire port diameter. With the present water model, stagnant or flowback conditions were not observed when video recordings of the dyed jets exiting the nozzles were examined. It is difficult to conjecture on the reasons of flowback because of its absence in this work but it might be produced when a nozzle port size is too large for a given flowrate.
Nozzle No. 5 with a downward port angle of 25° produces an improvement in surface pool quiescence when compared to the ones with an angle of 0°. This is explained by the greater proportion of fluid directed towards the bottom of the pool. Nozzle No. 6 with the horizontal tube projecting fluid towards the rolls also performs well. As cited earlier, its large port surface area reduces the velocity of the fluid entering the pool, as per Eq. (5), and this is accompanied by an even fluid distribution over the entire roll width. Both of these factors contribute to pool quiescence. An important result given by Fig. 5 is that for a twin roll caster, the geometry of the nozzle plays a greater role on level fluctuations than its immersion depth. This is caused by the geometry of the pool whose depth is substantially restricted by the rolls. With the present casting unit, the possible range of immersion depth was 15 to 45 mm. Considering that this is marginal, it is not surprising that geometry plays a greater role on level fluctuations than immersion depth. Among the geometric features investigated, those that affected flow direction were the most efficient promoters of quiescent surface conditions. This is illustrated by comparing nozzles No. 1 to 4, which produced the same flow directions, to nozzles No. 5 and 6, whose flow directions were distinct. The small size of the pool, $2 \times 10^{-3} \text{ m}^3$, appears to be the major factor explaining the susceptibility to nozzle flow direction. Another important geometric feature is the surface area of the port.

Figure 6 illustrates the distinct residence time distributions of the fluid from nozzles No. 1 and 6. In both cases, a peak in absorbance corresponding to the passage of the concentrated cloud of dye in front of the detector appears very early after the injection. The absorbance then undergoes an exponential decay with time that can be expressed in terms of first-order kinetics:

$$A = be^{-kt} \quad \text{...........................................(6)}$$

It can be noted that nozzle No. 1 produces an absorbance that decays more slowly than that of nozzle No. 6. For example, the former requires 36 s to reach an absorbance value of 0.1 while the latter takes 28 s. These results can also be described in terms of the rate constant, in Eq. (6), obtained from a regression analysis of the residence time distribution curve. In this case, the greater rate of decay is inferred by comparing the values of the rate constants shown in Fig. 6 to be 0.14 and 0.17 s$^{-1}$, for nozzles No. 1 and 6, respectively. The larger value obtained with nozzle No. 6 indicates that the residence time of the fluid in the upper portion of the pool is shorter. The fluid residing in that section of the pool is thus replaced by a newer one at a greater rate. In the prototype, this is desirable since skulls are less likely to form.

The difference between the two residence time distribution curves is attributed to the flow patterns produced by the nozzles. In discussing Fig. 3, it was mentioned that a large proportion of fluid bifurcated upwards when nozzle No. 6 was used. Although this observation is qualitative, it corroborates with the greater regeneration rate of fluid. Tests carried out with the other nozzles also corroborated with the qualitative proportions of fluid projected towards the upper portion of the pool. In Fig. 7, the fluid renewal times, $\tau$, produced by the nozzles listed in Table 2 are plotted as a function of immersion depth. Renewal time was defined as the time for the absorbance to reach a value of 0.1. It is intimately related to the rate constant because a small renewal time is produced by a rapid decay in the residence time distribution of the dye. It is observed that for nozzles No. 1 to 4, the renewal times are not significantly different. Even though nozzle No. 1 produces more surface agitation than nozzle No. 2, owing to its smaller diameter port, its renewal times are essentially the same. The change in port diameter alters the average velocity of the flow exiting the nozzle, as per Eq. (5), but not its distribution. Since both nozzles have essentially the same flow patterns, their renewal times are close to one another. The fluid from nozzle No. 5 takes a relatively long time to be renewed at the top of the pool since the downward angle of the ports directs a large proportion towards the bottom. Nozzle No. 6, performs best in terms of regenerating the upper portion of the pool. Also worth noting is that the effect of immersion depth on the values of renewal times is small compared to the geometry of nozzles.

The results presented in Figs. 5 and 7 show that for nozzles directing fluid towards the side dams, the port diameter should preferably be between 18 and 22 mm, and there is no
advantage to provide a sump. Having the ports at an angle of 25° downward is beneficial to reduce fluctuations at the pool surface but detrimental to regenerate the top of the pool with fluid. Nozzle No. 6, directing fluid towards the rolls is very efficient at simultaneously producing quiescent surface conditions and a high fluid regeneration rate in the upper region. Further tests were performed only with nozzles No. 2 and 6, the standard configuration of the former being a good basis to compare the latter. The effect of increasing the pool volume from $2.0 \times 10^2$ to $2.7 \times 10^2$ m$^3$ on level fluctuations is shown in Fig. 8 for various immersion depths. This corresponds to an increase in pool height of 196 to 216 mm. Since nozzle immersion depth is always given with respect to the water level, the nozzles had to be raised when the volume was increased. The increase in pool volume has a quieting effect on level fluctuations for both nozzles. As reported earlier, level fluctuations are not significantly affected by nozzle immersion depth and this is true at both pool volumes.

In Fig. 9, it is shown that for a given nozzle immersion depth, the fluid renewal times of the nozzles increase with pool volume. This is mostly explained by the effect the curvature of the mold has on the upper volume of the pool. From Figs. 8 and 9, it is seen that the reduction in level fluctuations provided by the increase in pool volume is at the cost of increasing the renewal time of the fluid. When casting liquid metal, consideration must also be given to the fact that increasing the pool volume leads to a greater contact time of the strip with the rolls if the caster speed is not adjusted accordingly. The strip temperature will be altered and this may considerably modify thermal stresses. Changes in pool volume have therefore effects on fluid dynamics as well as heat transfer. The latter cannot be evaluated with the present model but may be with mathematical modeling.

The flowrate of fluid feeding the pool is another process parameter having a strong influence on the pool behavior. The effect of its increase from $3.0 \times 10^2$ to $3.5 \times 10^2$ m$^3$/s on level fluctuations is shown in Fig. 10. For the strip caster at the Industrial Materials Institute, this approximately corresponds to an increase of the casting speed from 10 to 20 m/min. Taking each nozzle individually, these fluctuations are greater at the larger flowrate, which is what should be expected. Interestingly, nozzle No. 6 produces less fluctuations at a flowrate of $3.5 \times 10^2$ m$^3$/s than nozzle No. 2 at the lower flowrate of $3.0 \times 10^2$ m$^3$/s and is also less affected by the increase in flow rate. The reason of its superior performance is considered to be produced by the more even distribution of fluid in the pool. A similar pattern is seen in Fig. 11 for the effect of flowrate on the renewal times. When casting liquid metal, the increase in level fluctuations produced by the greater flowrate may not necessarily be
detrital to the surface quality of the strip if the casting speed is augmented. The contact location between the metal and the rolls has been reported to lie further from the top of the pool when speed is increased and solidification is less affected by surface agitation.\textsuperscript{34}

The power of the fluid entering the pool may be estimated by considering the kinetic energy per unit of time as the fluid exits a nozzle:

\[
P = \frac{1}{2} \rho \dot{E} A_b \]

(7)

The above expression has also been used in the case of a gas injected into liquid metal by a tuyere.\textsuperscript{38} A rate of dissipation of energy, \( \dot{e} \), may also be calculated\textsuperscript{38} from \( \dot{E} = P/M \) where \( M \) is the mass of fluid obtained from its density and the volume of the pool. An expression for the volume that accounts for the curvature of the mold has been published elsewhere.\textsuperscript{24}

The relationship between the renewal times and the rates of dissipation of energy is illustrated in Fig. 12. The flowrates were varied between \( 3.0 \times 10^{2} \) and \( 4.5 \times 10^{2} \) m\(^3\)/s to produce the energy dissipation rates shown in the abscissa. For copper, this corresponds to casting speeds between approximately 0.5 and 30 m/min. This Figure illustrates the superiority of nozzle No. 6 over No. 2 since a shorter renewal time is always produced for a given energy input. An attempt to correlate the rate of dissipation of energy to the amount of agitation provided by the level fluctuation measurements was also carried out. However, no significant statistical relationship was found but the reason may be that the level fluctuations in the present system are too small as well as on pool level fluctuations. At a given flowrate, increasing the volume of the pool had a quieting effect on the pool level fluctuations. At a given pool volume, increasing the flow rate decreased the residence time of the fluid but created greater level fluctuations. The exponential relations hips that renewal and mixing of a fluid could be driven by similar hydrodynamic mechanisms.

5. Conclusions

In twin roll casting, a high regeneration rate of the fluid near the top of the pool is desirable to prevent the formation of localized solidification (skulls). Provided that nozzles produce distinct flow patterns near this location, the fluid exiting these nozzles will also possess distinct residence time distributions from which replacement rates may be inferred. A quantitative tracer study with a water model was carried out to determine the residence time distributions produced by various nozzle geometries and process parameters. These measurements were combined with pool level monitoring to identify a nozzle that simultaneously provided high fluid regeneration rates and quiescent surface conditions.

On the basis of these two criteria, a nozzle having the full width of the rolls and directing fluid towards them is superior to those directing fluid towards the side dams. Providing a sump to a nozzle was observed to be superfluous. Immersion depth of the nozzles played a lesser role than geometry on the residence time distributions of the fluid as well as on pool level fluctuations. At a given flowrate, increasing the volume of the pool had a quieting effect on the surface of the pool but this was at the expense of increasing the residence time of the fluid in that vicinity. At a given pool volume, increasing the flow rate decreased the residence time of the fluid but created greater level fluctuations. The exponential relations hips that renewal and mixing times have with the rates of dissipation of energy were observed to be in the same range.

Nomenclature

\( A \): Absorbance
\( A_b \): Surface area of nozzle port (m\(^2\))
\( b \): Absorbance constant
\( D \): Diameter (m)
\( Fr \): Froude number
\( g \): Acceleration due to gravity (m/s\(^2\))
\( k \): Reaction rate constant (s\(^{-1}\))
\( L \): Characteristic length (m)
\( m \): Subscript for the model or mixing
\( M \): Mass of the fluid (kg)
\( n \): Exponent for the rate of energy dissipation
\( p \): Subscript for the prototype

\( \tau_r \): Renewal time
\( \tau_m \): Mixing time
\( \dot{E} \): Power of the fluid entering the pool
\( \rho \): Density of the fluid
\( P \): Power input (W)
\( Q \): Flow rate (m\(^3\)/s)
\( r \): Subscript for renewal
\( Re \): Reynolds number
\( t \): Time (s)
\( \bar{U} \): Average speed of the fluid (m/s)
\( We \): Weber number
\( \dot{e} \): Rate of dissipation of energy (W/kg)
\( \bar{\lambda} \): Scale factor
\( \mu \): Viscosity (Pa·s)
\( \rho \): Density of the fluid (kg/m\(^3\))
\( \sigma \): Surface tension (N/m)
\( \tau \): time (s)

**REFERENCES**

1) J. P. Birat: *Rev. Métall.*, *Can. Inf. Tech.*, 95 (1998), 1406.
2) H. Bessemer, US Patent no. 409,053, (1865).
3) T. Mizoguchi, K. Miyazawa and Y. Ueshima: *ISIJ Int.*, 36 (1996), 417.
4) K. Miyazawa, T. Mizoguchi, Y. Ueshima and S. Mizoguchi: Preprint No. 2 of the Int. Conf. on New Smelting Reduction and Near Net Shape Casting Technology for Steel, The Korean Inst. Met., Seoul, (1990), 745.
5) H. Yasunaka, K. Taniguchi, M. Kokita and T. Inoue: *ISIJ Int.*, 31 (1996), 417.
6) L. J. Heaslip, A. McLean and I. D. Sommerville: Continuous Casting, Vol. 1, ISS-AIME, Warrendale, PA, (1983), 67.
7) S. H. Seyedein and M. Hasan: Proc. of Int. Symp. on Computational Fluid Dynamics and Heat/Mass Transfer Modeling in the Metallurgical Industry, CIM, Montréal, QC, (1996), 146.
8) W. Blejde and R. Mahapatra: *Iron Steelmaker*, 28, (2001), No. 2, 43.
9) L. K. Chiang: Proc. of the Steelmaking Conf., Vol. 77, ISS-AIME, Warrendale, PA, (1994), 19.
10) T. Honeyands and J. Herbertson: *Steel Res.*, 66 (1995), 287.
11) J. Szekely and O. J. Jleibusi: The Physical and Mathematical Modeling of Tundish Operations, Springer-Verlag, New York, (1989).
12) M. Mohri, K. Onishi, K. Yamada and N. Nishimae: Thermec’97, Vol. 2, TMS, Warrendale, PA, (1997), 2185.
13) Y. K. Shin, T. Kang, T. Reynolds and L. Wright: *Ironmaking Steelmaking*, 22 (1995), No. 1, 35.
14) L. Strezo: US Patent no. 5, 720,336, (1998).
15) D. Bouchard, F. G. Hamel and B. Champagne: Thermec’97, Vol. 2, TMS, Warrendale, PA, (1997), 2217.
16) H. Fiedler, M. Jurisch, P. Preiss, R. Gödel, G. Sickert, H. Zimmermann, W. Neumann and R. Sellger: *Mater. Sci. Eng.*, A133 (1991), 671.
17) M. Yokumoto and H. Yamane: *ISIJ Int.*, 35 (1995), 778.
18) D. Jaffrey, I. Dover and L. Hamilton: *Met. Forum*, 7 (1984), 67.
19) N. A McPherson and S. L. McIntosh: Proc. of the Steelmaking Conf., Vol. 70, ISS-AIME, Warrendale, PA, (1987), 17.
20) Y. H. Wang: Proc. of the Steelmaking Conf., Vol. 73, ISS-AIME, Warrendale, PA, (1990), 473.
21) D. Bouchard, F. Busque and F. G. Hamel: Proc. of the Steelmaking Conf., Vol. 82, ISS-AIME, Warrendale, PA, (1999), 427.
22) L. I. Heaslip, I. D. Sommerville, A. McLean, L. Swartz and W. G. Wilson: Continuous Casting, Vol. 6, ISS-AIME, Warrendale, PA, (1992), 99.
23) A. Ferretti, M. Podrini and G. DiSchino: Proc. of the Steelmaking Conf., Vol. 68, ISS-AIME, Warrendale, PA, (1985), 49.
24) H. Nakato, K. Saito, Y. Ouchi, N. Namura and K. Sorimachi: Proc. of the Steelmaking Conf., Vol. 70, ISS-AIME, Warrendale, PA, (1987), 427.
25) N. T. Mills and L. F. Barharth: Continuous Casting, Vol. 1, ISS-AIME, Warrendale, PA, (1983), 85.
26) R. Sobolewski and D. J. Hurttuk: Continuous Casting, Vol. 6, ISS-AIME, Warrendale, PA, (1992), 73.
27) S. Tanaka, I. Suichi, S. Ogawa, T. Furuya, K. Sasaki and K. Yanagi: Proc. of the Steelmaking Conf., Vol. 74, ISS-AIME, Warrendale, PA, (1991), 809.
28) D. Xu, W. K. Jones and J. W. Evans: *Metall. Mater. Trans.*, 29B (1998), 1281.
29) D. Xu, W. K. Jones and J. W. Evans: *Modeling of Casting, Welding and Advanced Solidification Processes*, 8 (1998), 1145.
30) M. Hashio, M. Tokuda, M. Kawasaki and T. Watanabe: Continuous Casting, Vol. 6, ISS-AIME, Warrendale, PA, (1992), 63.
31) T. Teshima, M. Osame, K. Okimoto and Y. Nimura: Proc. of the Steelmaking Conf., Vol. 73, ISS-AIME, Warrendale, PA, (1988), 111.
32) D. Gupta and A. K. Lahiri: *Metall. Mater. Trans.* B25B (1994), 227.
33) D. Mazumdar and R. I. L. Guthrie: *ISIJ Int.*, 39 (1999), 524.
34) R. P. Tavares and R. I. L. Guthrie: *Can. Metall. Q.*, 37 (1998), 161.
35) B. G. Thomas, L. J. Mika, and F. M. Najjar: *Metall. Mater. Trans.*, 21B (1990), 387.
36) N. A. McPherson and A. McLean: Continuous Casting, Vol. 6, ISS-AIME, Warrendale, PA, (1992), 1.
37) R. I. L. Guthrie: Engineering in Process Metallurgy, Oxford University Press, (1993).
38) N. J. Themelis and P. Goyal: *Can Metall. Q.*, 22 (1983), 313.
39) J. Szekely, G. Carlsson and L. Helle: Ladle Metallurgy, Springer-Verlag, New York, (1989).
40) K. Krishnakumar, N. B. Ballal, P. K. Sinha, M. K. Sardar and K. N. Jha: *ISIJ Int.*, 39 (1999), 419.
41) D. Mazumdar and R. I. L. Guthrie: *ISIJ Int.*, 35 (1995), 1.
42) S. Asai, T. Okamoto, J. He and I. Muchi: *Trans. Iron Steel Inst. Jpn.*, 23 (1983), 43.
43) K. Nakamish, T. Fuji and J. Szekely: *Ironmaking Steelmaking*, 3 (1975), 193.