Design of a Submerged Entry Nozzle for Thin Slab Molds Operating at High Casting Speeds

Rodolfo D. MORALES,1)* Yong TANG,2) Gerald NITZL,3) Cristoph EGLÄEER2) and Gernot HACKL2)

1) Instituto Politecnico Nacional, Department of Metallurgy and Materials Engineering, Ed. 7 UPALM Col. Zacatenco, CP 07738 Mexico D.F. K&E Technologies President. E-mail: rmorales@ipn.mx
2) Researchers at RHI AG Technology Center, Satandort Leoben, Magnesitstraße, Leoben, A-8700 Austria, www.rhi-ag.com, E-mail: yong.tang@rhi-ag.com, christoph.egłaeer@rhi-ag.com, gernot.hackl@rhi-ag.com 3) Product Development Manager Flow Control, RHI AG, Vienna, Wienerbergstraße 11, Austria P.O. Box 143, Austria. E-mail: gerald.nitzl@rhi-ag.com

(Received on February 2, 2012; accepted on April 10, 2012)

A submerged entry nozzle (SEN) for thin slab casters operating at casting speeds as high as 7.5 m/minute was developed based on fundamental grounds of boundary-layer theory and water modeling experiments. Experimental techniques included tracer injection to observe overall fluid flow patterns, high speed video camera and image analysis to follow dynamic changes of meniscus levels and particle image velocimetry to measure water speeds in the mold. This design was compared with two other SEN designs of nozzles under current commercial use at various thin slab casters. Direct comparisons of mathematical simulations and experimental results among the three SEN’s evidenced that this new SEN yields very stable flows which are independent from casting speed and nozzle immersion depth. Fluid flow developed by this SEN consists of a double roll pattern without generation of superficial vortices. The two other SEN’s yield instable discharging jets due to and excessive shearing effects with the surrounding fluid inducing severe dissipation of kinetic energy which promotes severe tailing effects inducing strong meniscus oscillations. The proposed design has reported good industrial performances and a longer operating life because the slag protection belt suffers less wear thanks to smaller velocities of the bath in contact with the SEN wall.

KEY WORDS: thin slab; SEN design; turbulence; vortices; flow pattern; casting speed.

1. Introduction

The design of submerged entry nozzles (SEN) is critical for controlling steel flow turbulence in continuous casting molds. This is most important in thin slab funnel type molds, which operate at high casting speeds in confined volumes. Controlling turbulence is also important in order to avoid (1) mold flux entrainment which can transform to slivers in the final product2,3) (2) to avoid meniscus instability,4,5) (3) to evenly distribute heat transfer for uniform shell growth and (4) to attain steady flow conditions. Some slab casting submerged nozzle designs induce strong meniscus instability and high amplitude oscillations of liquid steel in the mold.6) Takatani et al.7) found that in a conventional slab mold the horizontal velocity under the meniscus fluctuates strongly. Using a physical model Yoshida et al.8) identified downward flows at the meniscus along the outer surface of the SEN due to the existence of differential pressure in this region. This descending flow carries down flux that, once reaching the port position, is easily entrained by the discharging jet into the steel bulk. The driving force for the descending flow is the instantaneous difference in meniscus velocity created by bath oscillations. Morales et al.9) reported that in a four port SEN strong backflows from the upper roll flow are responsible for the existence of strong bath oscillations. This indicates that full port utilization (FPU) is important for the development of new SEN designs.

Another factor for SEN design is the avoidance of high free shear strain rates induced by long discharging jets due to an increase in casting speed, as indicated by Torres-Alonso10) et al. Torres-Alonso et al. also reported the existence of energetic vortices formed very close to the SEN due to the existence of biased upper roll flows in a thin slab mold.11) Other authors claim that bath oscillations, specifically in thin slab molds, have their origin in an intermittent-confined cross-flow which passes through the gap located between the outer SEN wall and the wide mold wall.12,13) The highly-turbulent flow history of the fluid flow plays the most important role on energy dissipation and flow behavior. Indeed, the confined flow is a consequence of wall shear and strain rates generated by the walls of the SEN discharging ports as they shape the downstream jet into the mold. To support this hypothesis, more recently, Torres-Alonso et al.14,15) performed a detailed study explaining the mechanisms for the generation and dissipation rate of the turbulent kinetic energy through time scales analysis, physical modeling and mathematical simulations. These authors described a periodical dynamic distortion of the meniscus...
originated by an unbalance of the turbulent kinetic energy accompanied of positive velocity gradients along the discharging jets.

In the present work the authors focused on their effort in emphasizing the role of SEN design on turbulence control and meniscus stability by proposing a new design which is able to attain highly symmetric flows with even liquid distribution in the mold corners and a vortex-free bath surface. This novel design is based on the theoretical aspects of boundary layer and aerodynamics principles applied to steel flow through the SEN. This proposal pursues SEN optimization through low oscillation amplitude, a vortex-free bath surface, small meniscus velocities and homogenous flow distribution at the meniscus level in order to fulfill all user requirements at high casting speeds. In the present work a benchmarking study of different designs was undertaken.

2. Experimental Description of Water Model

Full-scale water modeling simultaneously satisfies both Reynolds and Froude similarity numbers and is the ideal and most realistic setup for thin-slab modeling. The geometry of this mold is referred to as a funnel mold type due to the rounded enlargement of the thickness in the middle section. This design allows the positioning of the submerged entry nozzle in the mold. The external profiles of the submerged nozzles, hereinafter referred to as SEN-1, SEN-2 and SEN-3, are shown in Fig. 1. SEN-1 has two lateral ports separated by a tall central divider. SEN-2 has also two lateral ports separated by a short central divider; SEN-3 has four ports, two lateral ones and two in the tip which are separated by long central divider. Main dimensions of these nozzles can be seen in Fig. 1. These three nozzles have interior thicknesses of 60 mm in the their tips and the thickness of the ceramic body in the same locations is 26 mm. Other dimensions can be seen in the mentioned figure.

The geometries of SEN-1 and SEN-3 were replicated into poured-thermoplastic material; the result was the generation of two plastic models of these SEN’s. Regarding SEN-2 an actual SEN was used in these experiments and therefore it was made of conventional alumina-graphite refractory with a zircon belt. A mold-SEN made of plastic set obtained through the operations described here can be seen in Fig. 2. The first two SENs were selected as benchmark cases for studying their capacity to cast steel at speeds of 5.5 and 7.5 m/min. SEN-3 is an optimized design aimed to accomplish the goals set above. Design of SEN-3, proposed as the most suitable nozzle to cast at high casting speeds, was derived from previous intensive Computer Fluid Dynamics (CFD) simulations using principles of boundary layer theory (mainly ratios between thicknesses of momentum and displacement layers and flow separation phenomena). The mold of plastic was mounted in a steel frame adjusted with sets of screws and bolts. To provide rigidity in order to counteract the water pressure two steel belts located at different heights were fixed around the mold as is seen in Fig. 2. In the pipe, which transports water from the main deposit to the mold, there is a flow meter and a rubber sealed injection inlet to introduce a red dye tracer into the main stream. This pipe is prolonged near the laboratory ceiling and descends later into the SEN through a 90° elbow. A circular sleeve in the top of the SEN allows a good fitting with the steel pipe to ensure mechanical stability and straightness.

Dynamics of water meniscus was monitored continuously by a Fast Speed Video Camera from Southern Video Systems Inc.*; one half of the mold just in the meniscus, forming a belt from the mold narrow face to the SEN wall, was the region of interest. Actually, a recording speed of only 30 frames per second (FPS) was good enough to follow details of meniscus height variations with time for some given experimental conditions. This recording frequency did not demand large computer memory permitting very good recordings with high resolution of meniscus features. The meniscus profile of each one of the video images obtained was used to calculate the height of the standing waves in the mold generated by the water input through the SEN using the static water level as level reference zero. Those meniscus profiles were characterized and plotted using the image analysis software Origin. Conventional video recordings were also used to study mixing patterns of tracer injected in the SEN.

Finally, fluid flow was also studied using Particle Image Velocimetry (PIV) equipment from DANTEC **. In this

---

* Southern Vision Systems Inc. Madison Blvd. Suite 150, Madison AL.
** Danvac Dynamics Inc. 750 Blue Point Rd., Holtsville, NY 11742
equipment coupled charged devices (CCD) capture images of seeding particles, neutral-buoyant in water, interacting with a laser sheet and the signals are processed through Fast Fourier Transforms to obtain velocity fields as it is described in references (18) and (19). In each case two submersion depths were evaluated, 220 mm (shallow position) and 350 mm (deep position), which were measured from the meniscus level to the bottom of each SEN. The experimental matrix and mold dimensions for the water modeling trials can be found in Table 1.

3. Mathematical Model

In order to follow the instantaneous velocities the Large Eddy Simulation20 model is employed, in this model the instantaneous velocity is the sum of the filtered velocity and the residual velocity. The Navier-Stokes equations are filtered by a box type filter permitting the simulation of large scale eddies. The size of the filter is equivalent to the size of the computational grid, $\Delta$. Therefore, applying the filtration operation the Navier-Stokes equations are transformed in:

**Continuity:**
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho \overline{u}_j \right) = 0 \quad \text{.................. (1)}$$

**Momentum:**
$$\frac{\partial}{\partial t} \left( \rho \overline{u}_j \right) + \frac{\partial}{\partial x_i} \left( \rho \overline{u}_j \right) = - \frac{\partial \rho}{\partial x_j} + \frac{\partial\overline{p}}{\partial x_j} + \rho g \quad \text{.................. (2)}$$

The effect of small scales (sizes $< \Delta$) is modeled through the stresses calculated by filtered velocities according to;

$$\tau_{ij} = \overline{u}_i \overline{u}_j - \overline{u}_i \overline{u}_j \quad \text{........................ (3)}$$

The standard sub-grid model is that proposed by Smagorinsky21 and is given by,

$$\tau_{ij} = \left( \overline{u}_i \overline{u}_j - \overline{u}_i \overline{u}_j \right) + \left( \frac{\overline{u}_i \overline{u}_j}{\Delta} \right) + \frac{\overline{u}_i \overline{u}_j}{\Delta} \quad \text{........... (4)}$$

The filter operation applied on flow variables is indicated by the over-bars. These stresses are equivalent to the Reynolds stresses that result from time or ensemble averaging of the advection fluxes, but differ in that they are consequences of special averaging and tend to zero if the filter width, $\Delta$, tends to zero too. The most common used sub-grid scale models are based on the gradient transport hypothesis which correlates $\tau_{ij}$ with the large scale strain-rate tensor;

$$\tau_{ij} = -2\nu \overline{S}_{ij} + \frac{\partial}{\partial x_i} \left( \frac{\partial \overline{u}_j}{\partial x_j} \right) \quad \text{.................. (5)}$$

Where $\tau_{ik} = \overline{u}_i \overline{u}_j$ and $\overline{S}_{ij}$ is given by,

$$\overline{S}_{ij} = \frac{1}{2} \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} \right) \quad \text{.................. (6)}$$

In this model (LES) and eddy-viscosity proportional to the local large-scale deformation rate is proposed according to,

$$\tau = \left( C_s \Delta \right) \left| \overline{S} \right| \quad \text{.................. (7)}$$

Where $C_s$ is the Smagorinsky’s constant and the tensor $\left| \overline{S} \right|$ is given by;

$$\left| \overline{S} \right|^2 = \left( 2 \overline{S}_{ij} \overline{S}_{ij} \right) \quad \text{.................. (8)}$$

Smagorinsky’s constant is evaluated considering the 5/3 law of the internal range spectrum of energy;

$$E(k) = \frac{2}{\alpha \Delta} \frac{k_0^5}{k^{5/3}} \quad \text{.................. (9)}$$

The magnitude of $\left| \overline{S} \right|$ can be evaluated by integrating the spectrum over all resolved wave numbers:

$$\left| \overline{S} \right|^2 = \int_0^{\frac{\pi}{\Delta}} k^5 E(k) dk \quad \text{.................. (10)}$$

or

$$\left| \overline{S} \right|^2 = \frac{3}{2} \frac{2}{\alpha \Delta} \frac{\pi^3}{k^{5/3}} \quad \text{.................. (11)}$$

With $\alpha = 1.41$, this yields,

$$C_s = \frac{1}{\pi} \left( \frac{2}{3\alpha} \right)^{3/2} \left( \frac{\pi}{\Delta} \right)^3 \approx 0.18 \quad \text{.................. (12)}$$

3.1. Initial and Boundary Conditions

Initial and boundary conditions involved uniform plug flow through the body of the SEN. Boundary conditions to solve Navier-Stokes equations include no-slip on walls and zero momentum flux through walls. To estimate the velocity at the first node of the grid near a wall, the wall function was employed together with a damping function proposed by Dries22 in order to estimate the distance from the wall inside the boundary layer. Pressure boundary condition of 101 325 Pa was fixed at the strand.

The 3D domain of the simulation included the whole submerged entry nozzle and the mold. The mesh size ranges from 2 mm to 5 mm and the total number of nodes in the grid was approximately 1.3 million. Various combinations of casting speeds and immersion depths, as shown in Table 1, were investigated. The flow field in the mold was computed by solving the continuity and momentum conservation equations in the three-dimensional domain with the

| Table 1. Experimental Conditions and Mold Dimensions. |
|-----------------------------------------------|
| Casting Conditions | Casting Speed of 5.5 m/minute | Casting Speed of 7.5 m/minute |
| Immersion depth of 220 mm | A | C |
| Immersion depth of 350 mm | B | D |
| Mold Dimensions | |
| Thickness | 60 mm |
| Bulge (funnel) width at mold top | 880 mm |
| Mold height | 920 mm |
| Bulge (funnel) internal radius at mold-copper top | 1 515 mm |
| Mold width | 1 372 mm |
| Length of bulge (funnel) | 850 mm |
LES model described above. The set of governing equations were discretized using the finite volume technique in a computational domain and solved with the help of above boundary conditions using the algorithm SIMPLE\(^2\) (Semi-Implicit Method for the Pressure-Linked Equations) to resolve the pressure–velocity coupled in the momentum equation. A criterion for convergence was set as the condition when the sum of all residuals of flow variables is equal to \(10^{-5}\).

4. Results and Discussion

Dye injections and Particle Image Velocimetry (PIV) were employed in order to characterize the flow pattern for each of the SENs. The dye injection simulated plug flow from the SEN into the mold and also gave a good representation of mixing behavior. Image sequences were captured for both the initial dye injection and a subsequent period of steady-state flow. The images from the water modeling experiments were processed using image-processing software. The results for numerical and water modeling were compared accordingly. Here the most representative results are described and discussed.

4.1. Fluid Flow Overview

Figures 3(a)–3(c) give an overview of the fluid flow, visualized through dye injection experiments, corresponding to SEN-1, SEN-2 and SEN-3, at immersion depths of 220 mm and a casting speed of 7.5 m/min. As seen in Fig. 3(a), SEN-1 provides an upper roll flow without generating an active lower roll flow and creates a stagnant large zone below the nozzle bottom. The meniscus analysis shows heavy depressions at the position of the funnel, inducing the formation of vortices. Similarly, SEN-2 also induces a strong single upper roll flow but without a stagnant zone below the nozzle bottom. However, the presence of severe meniscus depressions remains, thus indicating instability at the position of the funnel. The flow pattern for SEN-3 is shown in Fig. 3(c). SEN-3 induces a typical active double roll flow in the upper and lower parts of the mold. Moreover, SEN-3 maintains a stable meniscus without the formation of strong vortices or depressions.

For SEN-1 and SEN-2 the two different immersion depths show distinctive differences in terms of the resulting flow pattern, as shown in Figs. 4(a) and 4(b), for a deeper immersion, respectively. In the case of SEN-1 the stagnant zone below the nozzle bottom is decreased. However, the meniscus depression still remains, indicating the presence of surface vortices. At immersion depth 350 mm the flow pattern for SEN-2 experiences more radical changes, since large stagnant zones exist in the mold corners due to non-symmetric dye mixing behavior. In contrast with the other
two SENs, SEN-3, shown in Fig. 4(c), maintains the double roll flow pattern without leaving stagnant zones and without depressions on the meniscus surface. Therefore, it is evident that SEN-3 provides stable flows which are independent from the immersion depth.

4.2. CFD Analysis of Meniscus Stability

Meniscus stability was simulated through CFD under unsteady state conditions using the criterion of the resultant 3-D fluctuating-velocity vector. This velocity vector is used as a monitoring spot for fluctuating velocities. It is positioned 10 mm below the meniscus at the position of the mold funnel for SEN (spot M-n-1 in Fig. 5). The position of this monitoring spot was chosen because it is just in the transition zone between the straight parallel wide molds and the funnel where the flow is more instable as has been reported in other works.\(^{14,15}\) Figures 6(a)–6(c) show the history of instantaneous velocities at the monitoring spot for SEN-1, SEN-2 and SEN-3, respectively, at a casting speed of 7.5 m/min. Figures 7(a)–7(c) corresponds to instantaneous velocity magnitudes at the casting speed of 5.5 m/min. As it is expected, the magnitudes of the instantaneous velocities for the high casting speeds are larger than for the low casting speeds. The comparison of results between Figs. 6(a)–6(c) lead to the following observations:

- SEN-1 creates the highest instantaneous velocities, reaching magnitudes as high as 0.90 m/s. This conveys a high probability for flux entrainment under actual casting conditions. Low velocities, such as 0.03 m/s, are also observed. The average amplitude of the velocity is 0.38 m/s.
- SEN-2 is similar to SEN-1, with a low frequency of

Fig. 5. Monitoring point near the meniscus level for CFD simulations.

![Monitoring point near the meniscus level for CFD simulations.](image)

Fig. 6. Velocity magnitude history at monitoring spot near the meniscus of liquid for three different SEN designs (casting speed: 7.5 m/min, immersion depth: 220 mm).

(a) SEN-1

(b) SEN-2

(c) SEN-3

Fig. 7. Velocity magnitude history at monitoring spot near the meniscus of liquid for three different SEN designs (casting speed: 5.5 m/min, immersion depth: 220 mm).

(a) SEN-1

(b) SEN-2

(c) SEN-3
wide velocity variations. The average amplitude of the velocity is 0.39 m/s. Meanwhile, the highest velocity spike is around 0.75 m/s.

- SEN-3 with a more stable meniscus creates average velocity amplitude of 0.23 m/s, which is considerably smaller than the other two designs.

At the lower casting speed SEN-3 shows the most stable meniscus with smaller velocity oscillations. SEN-3 is much more stable than SEN-2 and SEN-1 ensuring, eventually, a better slab quality. At casting speeds like 5.5 m/min, SEN-2 yields velocity spikes as high as 0.75 m/s, SEN-2 yields maximum fluctuating velocities of 0.6 m/s and SEN-3 yields maximum fluctuating velocities of 0.4 m/s.

**Figures 8(a)–8(d),** taken at increments of one second, show the dynamic changes of velocity fields in the central plane of the mold for SEN-1 at the shallow immersion depth and a casting speed of 7.5 m/min. As seen in Figs. 8(a)–8(d), the discharging jets have a long residence time with respect to the surrounding fluid. If the lengths of the jets are approximately in the same order of magnitude as the containing vessel length, as in the present case, highly unstable flows are generated. Such conditions arise because the jets generate shear strains on the surrounding fluid, forming intermittent boundary layers which are unstable. This instability leads to frequent jet oscillations, jet rupture and jet separation. Figures 8(a)–8(d) also show that when both jets oscillate, due to an asymmetric flow pattern, high fluid velocities near the meniscus are induced, thus endangering the slab quality due to possible flux entrainment problems.

**Figures 9(a)–9(d) show the corresponding fluid flows for SEN-2 and close similarity is found with those of SEN-1, regarding the dynamic behavior of both discharging jets.** Meanwhile, **Figs. 10(a)–10(d) show the dynamic behaviors** of the discharging jets with SEN-3. As observed in the present case, the discharging jets are short and therefore their interaction lengths with the surrounding flow is limited. This decreases the shearing stresses and the possibility of jet breakage and dispersion.

In order to measure water meniscus fluctuations with different SENs, image processing was used to analyze the wave height as is described above. **Figure 11(a) shows the averaged wave amplitude on the mold surface. The standard deviation of wave amplitude (stdev) is shown in Fig. 11(b).**
Figure 11(a) suggests that among all the SEN profiles, SEN-3 has the smallest average wave amplitude for shallow immersion (A and C). The wave amplitude is reduced significantly for SEN-1 and SEN-2 changing the immersion depth from 220 mm to 350 mm (conditions A to B, C to D). For SEN-3 the wave amplitude decreases only slightly when deeper immersed indicating that SEN-3 is less sensitive to the immersion depth changes. As seen in Fig. 11(b), this nozzle provides larger standard deviations than SEN-2, however, it should be noticed that this later SEN provides flows too much oriented downwards providing a stable meniscus at expenses of large stagnant regions in the upper side of the mold. Then smaller standard deviations yielded by SEN-2 are misleading data as this simply means large unused mold volumes. Therefore, SEN-3 provides the most stable flow conditions during the ramping process within a casting sequence.

Figure 12 shows the wave amplitudes, representing a topographical history of the mold surface wave. These topographies express the surface wave fluctuations with respect to time across all three designs and are derived from captured images obtained through the water model experiments. For comparison, only mold surface waves on one side of the nozzle are shown in the picture. The red color indicates the peak of the meniscus and the blue color indicates a valley or depression in the meniscus. Areas shown in green are those that maintain a relatively static or neutral meniscus level.

It is evident that the use of SEN-1 results in the highest wave heights and fluctuations, indicated by the more continuous presence of red peaks, particularly near the meniscus level close to the narrow face of the mold. Level fluctuations in the area close to the SEN also present high magnitudes. In the actual caster such conditions would eventually lead to the entrainment of flux. The larger presence of green areas in SEN-3 indicates a more stable meniscus. It is also important to emphasize the different frequencies of meniscus oscillations comparing the SENs. For example, waves changing with time in the case of SEN-1, have the largest wave lengths and amplitudes, followed by SEN-2 and SEN-3.

4.3. PIV Measurements

Since there is an evident relation between the dynamic behavior of meniscus oscillations and velocity fields, this relationship will be discussed in this section. One important note is that the casting conditions have a clear influence on changing the fluid flow pattern thus also affecting heat transfer of steel in the mold, which also affects the solidification. For example, Fig. 13(a) shows the fluid flow pattern of SEN-2 analyzed by PIV measurements for a casting.
speed of 7.5 m/min at the shallow immersion depth of 220 mm. A typical upper roll flow can be seen in this PIV measurement. However, when the SEN is more deeply immersed, thereby keeping the same casting speed, the related change in flow pattern is shown in Fig. 13(b). In this case the momentum transfer towards the narrow mold wall is considerably decreased, causing the steel flow towards the bottom part of the port. This condition leaves a very large stagnant zone, from the upper edge of the port to the mold corner, hereby, there is a very slow motion in the meniscus yielding smaller standard deviations of wave amplitude as was discussed above. When using SEN-3 in both immersion depths, the flow pattern does not undergo radical changes as is clearly evident in Figs. 14(a) and 14(b). Moreover, it has been tested in plant trials the improved meniscus stability resulted in longer life of the submerged entry nozzles due to reduced slag line wear in the order of 21% (See Fig. 15).

5. Conclusions

Water modeling experiments and mathematical simulations of fluid dynamics on meniscus stability of a thin slab casting mold have been carried out. By comparing three high-performance SENs a benchmark study was completed. The first SEN has two ports and a long central divider, the second SEN has also two ports and a short central divider. Finally, the SEN proposed here as a candidate to cast at high casting speeds has four ports, two of them in the tip and two lateral ports. All studies performed resulted in the following conclusions:

(1) The fluid flow pattern of liquid steel inside the mold created with the four ports SEN is more symmetric than those provided by the other two SENs.

(2) The amplitudes of the velocity fluctuations at the meniscus level are the smallest using the four ports SEN followed by the SEN with two ports-short central divider and finally the SEN with two ports and a large central divider.

(3) The fluid flow pattern of liquid steel provided by SEN with four ports is relatively independent of the SEN immersion depth. Especially for the SEN with two ports small central divide the flow pattern is highly dependent on the immersion depth.

(4) Statistical analysis of wave amplitudes measured in the water model indicates that the smallest standard deviations and average wave amplitudes are found with the four ports SEN. The four ports SEN induces smaller meniscus oscillations of lower amplitude and higher frequency than the other two SENs.

(5) The four ports SEN is recommended as the best choice to cast steel in modern thin slab casters at high cast-
Laminarization speeds and with wide variations of immersion depths.

Acknowledgements

The authors give the thanks to RHI AG for supporting this development, one of the authors (RDM) gives the thanks to the institutions CoNaCyT, SNI and IPN for their continuous support to his research group.

REFERENCES

1) S. Feldbauer and A.W. Cramb: 13th PTD Conf. Proc., ISS, Warrendale, PA, (1997), 327.
2) W. H. Eming and T. Waugaman: Steelmaking Conf. Proc., ISS, Warrendale, PA, (1994), 371.
3) S. Kumar, B. N. Walker, I. V. Samarasekera and J. K. Brimacombe: 13th PTD Conf. Proc., ISS, Warrendale, PA, (1997), 119.
4) E. Torres-Alonso, R. D. Morales, S. Garcia-Hernandez, A. Najera-Bastida and A. Sandoval Ramos: Metall. Mater. Trans. B, 39B (2008), 840.
5) R. D. Morales: Proc. 15th Steelmaking Conf., Instituto Argentino de Siderurgia, Sn. Nicolás, Argentina, (2005), 253.
6) M. Suzuki and M. Nakada: ISIJ Int., 41 (2001), 670.
7) K. Takatani, Y. Tanizawa, H. Mizukami and K. Nishimura: ISIJ Int., 41 (2001), 1252.
8) J. Yoshida, T. Ohmi and M. Iguchi: ISIJ Int., 45 (2005), 1160.
9) R. D. Morales, J. Palafox-Ramos, L. Garcia-Demedices and R. Sanchez-Perez: ISIJ Int., 44 (2004), 1384.
10) E. Torres-Alonso, R. D. Morales, L. G. Demedices, A. Nájera, J. Palafox-Ramos and P. Ramirez-Lopez: ISIJ Int., 47 (2007), 679.
11) E. Torres-Alonso, R. D. Morales, J. Palafox-Ramos and P. Ramirez-Lopez: Steel Res. Int., 79 (2008), 553.
12) M. R. Davidson and N. J. Lawson: Proc. 2nd Int. Conf. on CFD in the Minerals and Process Industries, CSIRO, Canberra, Australia, (1999), 223.
13) N. J. Lawson and M. R. Davidson: J. Fluids Eng. ASME, 124 (2002), 535.
14) E. Torres-Alonso, R. D. Morales, S. Garcia-Hernandez and J. Palafox-Ramos: Metall. Mater. Trans. B, 41B (2010), 583.
15) E. Torres-Alonso, R. D. Morales and S. Garcia-Hernandez: Metall. Mater. Trans. B, 41B (2010), 675.
16) H. Schlichting: Boundary-Layer Theory, McGraw Hill Books Co., New York, London, (1979), 609.
17) www.onginelab.com, (accessed February 2nd, 2012).
18) R. Sanchez-Perez, R. D. Morales, M. Diaz-Cruz and O. Olivares: ISIJ Int., 43 (2003), 637.
19) R. Sanchez-Perez, R. D. Morales, L. Garcia-Demedices and M. Diaz-Cruz: Metall. Mater. Trans. B, 35B (2004), 85.
20) P. Sagaut: Large Eddy Simulation for Incompressible Flows, 2nd ed., Springer-Verlag, Berlin, (1998), 31.
21) J. Smagorinsky: Monthly Weather Rev., 91 (1963), 99.
22) E. R. Van Driest: J. Aerospace Sci., 23 (1956), 1007.
23) T. Chung: Computational Fluid Dynamics, 1st ed., Cambridge University Press, Cambridge, London, UK, (2000), 696.
24) M. Suzuki, M. Suzuki and M. Nakada: ISIJ Int., 41 (2001), 670.