Behavior and Removal of Inclusions by Means of the Use of Mathematical and Physical Simulations as Well as the Measured Vibrations with an Accelerometer in a Funnel Mold in Thin Slab Continuous Casting

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Due to the inherent difficulty in making direct observations of the behavior of the dynamic flow of liquid steel and the inclusions in the continuous casting of the steel, mathematical and physical modeling, having great popularity and acceptance, has been an invaluable aid to the understanding of the fluid flow phenomena. Up to date, there is little information available in the literature regarding the behavior of the inclusions, especially inside the funnel type mold.

It has been found that the accelerometer is a transducer capable of relating the vibration with the behavior of the inclusions in the continuous casting mold. It was indicated that higher levels of vibration in the thin slab mold is greater than the removal of inclusions therein.

As a starting point of the results a mathematical modeling, previously carried on the work group, were used,1) where an analysis of the fluid flow process of the continuous casting thin slab was carried out. Two nozzle designs, two depths of 22 and 34 cm, and three casting speed of 4, 5 and 6 m/min were simulated. In all cases, just 100 particles were simulated within the flowing liquid metal, because once the mathematical calculations or the processing time increases as the quantity of particles grow. These have previously been treated with a liquid, sensitive to the black light, and then under this type of light the inclusions are luminescent. All cases were also solved in the simulation software Fluent® where a slag layer, in which all the inclusions that reach it are trapped, is generated at the meniscus of liquid metal.

The area near the nozzle has a greater concentration of particles, which is due to low speed or flow pattern change in said zone. These inclusions are floating in this area eventually become stripped and trapped in the slag layer.

KEY WORDS: nozzle; mathematical and physical simulation; inclusions; slag; casting speed; accelerometer and continuous casting mold.

1. Introduction

It is considered that the forces acting on the mold are gravitational2,3) as the standard Froude number can be satisfied at any scale in a model with water. It is also considered that all measures of the holes and hydraulic heights used in the system were varied according to a single scale parameter, this because the kinematic viscosity of the liquid steel at the process temperature (1 600°C) and water, are virtually identical. Since the difficulty of observing the flow of the liquid steel directly, physical modeling has been a tool used to study the phenomena that occurs on different steelmaking processes. This allows quantifying the performance of the mold to float non-metallic inclusions.

Removal of inclusions from molten steel are based on the use, among others, of the buoyant forces when steel is agitated with inert gas in the step of secondary refining. This method, however, does not work well for inclusions in the order of micrometers, so that the terminal velocity of the inclusions depends on a certain critical mass and therefore require a longer processing time for their elimination. This time that can not be disposed in the secondary refining.

The present research work is focused on analysis of the behavior of inclusions in a thin slab continuous cast mold, funnel type, and observation of the possibility to eliminate them. Physical and mathematical simulation is performed on the assumption with the redesign of a nozzle, which is currently used in a Mexican company (Ternium). By varying both the depth of it and the casting speeds, it was considered that greater removal of inclusions will possibly, becomes within the liquid steel and then they will be trapped in the
layer of lubricant powder (slag).

2. Experimental Methodology

The experimental phase of this study was based on the analysis of the results of the mathematical modeling presented in reference,\(^1,6)\) both the nozzle and the mold for the continuous casting of thin slab funnel type. For the main goal of this research work, it will focus on the latter stage, i.e. physical modeling.

2.1. Physical Modeling

For physical modeling, a model of the mold and nozzle was designed based on the appropriate scale similarity criteria where liquid metal flow is simulated with water. If the water flow in the model is a realistic representation of the actual flow in the mold, it can be used to study various aspects of the flow into the mold, including:

1. Deformation of the free surface and surface turbulence;
2. Viewing flow in different areas of the mold with a tracer;
3. Transport, flotation and simulation of inclusions;
4. Vorticity formation on the metal-slag interface and slag entrapment into the bosom of the liquid metal in the mold.
5. Energy dissipation, etc.

To study the behavior of the fluid flow, a physical model a 1/2 scale of the actual mold continuous casting of thin slab funnel-like clear acrylic 12 mm thick, was fabricated and a submerged entry nozzle SEN of complex geometry was manufactured in high density resin. The refractory thickness was maintained in order to respect the original nozzle dimensions. The mold was designed to work with a speed of up 8 m/min which is equivalent to 84.34 liters/min of water. In Fig. 1 the dimensions of both the nozzle and the mold\(^6)\) are shown.

2.2. Vibration Monitoring

One of the best way to visualize the performance of the continuous casting mold is monitoring it with transducers. In this research work, the main purpose, with the use of accelerometers, is to follow the evolution of the flow pattern generated on one of the thin mold walls, and also to correlate this pattern with the removal of inclusions in the mold in an indirect way. The principle is that by the energy of impact on the mold walls due to fluid flow, vibration occurs and therefore can be followed up to its elimination. An accelerometer, whose sensitivity is 1.014 mV/g in a frequency range of 2.5 to 300 Hz, is used. The accelerometer signals are digitized with a Data AcQuisition (DAQ) card; 24-bit resolution, four differential channels and a maximum sampling rate of 51.2 K samples per second per channel. The accelerometer was placed at four different points.

In Table 1 the distances from the mold top are shown, according to the scale used for physical simulation (1 to 1/2) and for the mathematical simulation (1 to 1). These points were selected, based on the results of the mathematical simulation. In Fig. 2 these points are shown and it will be the reference for future analysis.

Programs were written in graphical programming environment, LabVIEW™. A signal pattern is taken, and then natural noise of the system is subtracted numerically to the

<table>
<thead>
<tr>
<th>Transducer Position</th>
<th>Physical Simulation (m)</th>
<th>Mathematical Simulation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M (Meniscus)</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Point 4 (P4)</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>Point 3 (P3)</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>Point 2 (P2)</td>
<td>0.38</td>
<td>0.76</td>
</tr>
<tr>
<td>Point 1 (P1)</td>
<td>0.55</td>
<td>1.1</td>
</tr>
<tr>
<td>ME (Mold End)</td>
<td>0.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic geometries for the physical modeling: a)–b) the funnel thin slab mould, c)–d) the SEN, e) internal SEN-original, and f) internal SEN-modified.\(^6)\)
digitized transducer signal. Two programs were written; one for the digitization stage of signals from the accelerometer and the other one for the post-processing phase. In the latter program, the area is calculated under the curve of the signal depending on the conditions of the simulation. By this procedure, depending on the casting it will be the magnitude of the signal. These vibrations are compared to the data obtained from the phase of image processing where the inclusions, trapped in the slag and within the metal, are quantified.

The simulations were carried out with the casting speeds and flows as shown in Table 2. The values of casting speeds and flows were based on the scale and dimensionless numbers chosen for the constructed simulation model. Another important parameter is the depth of immersion of the nozzle, for this case only one depth was used; depth in the prototype is 34 cm and due to the scale factor in the model are 17 cm respectively.

2.3. Inclusions Simulation

Since the non-metallic inclusions in the liquid steel are lighter, they can float to the surface. For a range of sizes of inclusions reaching the continuous casting mold, it can be assumed that the inclusions float according to the Stokes velocity law. Using the relevant dimensionless numbers will reach to an equation in which the radius of the inclusion can be calculated with Eq. (1) and by substituting the values of Table 3 in this equation a relationship between the radius of the prototype inclusion and model inclusion, can be obtained from Eq. (2):

\[ R_{inc,m} = \left( \frac{2}{\pi} \right)^{0.25} \left( \frac{1 - \frac{\rho_{inc,p}}{\rho_m}}{1 - \frac{\rho_{inc,m}}{\rho_m}} \right)^{0.5} R_{inc,p} \]  
\[ R_{inc,m} = \left( \frac{0.5^{0.25}}{\pi} \right)^{0.25} \left( \frac{\frac{3.4}{7.4}}{1 - \frac{0.974}{1}} \right)^{0.5} R_{inc,p} = 2.5 R_{inc,p} \]  

Using a prototype inclusions ranging from 50 to 100 microns, a calculation of the model inclusions was made based on Eq. (2). The reason why the range used is that ones most likely to be eliminated, but smaller are almost impossible to remove. Also this fact has a nothing-significant effect on the quality of the slab, the size distribution of inclusions are shown in Table 5.

2.4. Physical Simulation

All the experiments were carried out in the acrylic model, as shown in Fig. 1, and the cast speed, flow of water, the diameter and the amount of the inclusions per gram are presented in Table 5.

Inclusions made with the acrylic material, which was subjected to grinding, classification and impregnation with penetrant inspection fluorescence dye, were prepared. In this way the particles can be viewed under black light. Several black light lamps were placed around the mold and in the discharge area of the nozzle to observe more clearly the injected inclusions. A digital camera to obtain images of the inclusions was used during its evolution into the mold and

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**Table 2.** Parameters used in the simulation physical and mathematical.

<table>
<thead>
<tr>
<th>Speed (m/min)</th>
<th>Flow (liters/min)</th>
<th>Velocity (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>49</td>
<td>53.9</td>
</tr>
<tr>
<td>5</td>
<td>61.2</td>
<td>67.4</td>
</tr>
<tr>
<td>6</td>
<td>73.4</td>
<td>80.8</td>
</tr>
</tbody>
</table>

**Table 3.** Parameters for the calculation of model inclusions.

<table>
<thead>
<tr>
<th>Density, of the inclusion model</th>
<th>Water density</th>
<th>Density, of the prototype inclusion</th>
<th>Steel density</th>
<th>Inclusion prototype radius (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Acrylic g/cm³)</td>
<td>(g/cm³)</td>
<td>(g/cm³)</td>
<td>(g/cm³)</td>
<td>(μm)</td>
</tr>
<tr>
<td>0.974</td>
<td>1</td>
<td>3.4</td>
<td>7.4</td>
<td>50–100</td>
</tr>
</tbody>
</table>

**Table 4.** Relationship between: prototype inclusions and model inclusions.

<table>
<thead>
<tr>
<th>( R_{inc,p} (μm) )</th>
<th>( R_{inc,a} (μm) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>125</td>
</tr>
<tr>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>70</td>
<td>175</td>
</tr>
<tr>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>90</td>
<td>225</td>
</tr>
<tr>
<td>100</td>
<td>250</td>
</tr>
</tbody>
</table>

**Table 5.** Physical model parameters.

<table>
<thead>
<tr>
<th>Velocity (m/min)</th>
<th>Water flow (liters/min)</th>
<th>Inclusion Diameter (μm)/Amount of particles per gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>49</td>
<td>250/125 500</td>
</tr>
<tr>
<td>5</td>
<td>61.2</td>
<td>210/211 730</td>
</tr>
<tr>
<td>6</td>
<td>73.4</td>
<td>177/353 600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>110/475 00</td>
</tr>
</tbody>
</table>
the slag layer. The resolution of these was of 1,270 × 720 p.

Because the amount of particles are huge, for the purpose of this research work it was arrived to the conclusion that in this model 0.01 grams was enough to be in the range of 14,000 to 40,000 particles as in the industrial prototype. Two nozzle depths were used in this set of experiments. The depth in the prototype were 22 and 34 cm and due to the scale factor in the model were 11 and 17 cm respectively. The inclusions must be previously prepared with a dispersant in order to avoid any agglomeration when they are injected. Once the flow is leveled and there are no bubbles in the nozzle, the particles are injected.

Trials in the model last about 50 seconds, long enough to know how many inclusions were removed on the surface and trapped in the slab. In order to know the removal ratio, the inclusions are weighed and then a relationship is established with the injected ones. It was very important in this stage to wash the inclusions to remove any oil traces in order to eliminate any error in the final weight. Once the inclusions are weighed the following formula is used to calculate the percentage of the removed inclusions:

\[ \text{Removal ratio} = \frac{\text{trapped inclusions}}{\text{injected inclusions}} \times 100 \quad \text{..... (3)} \]

Thus a comparison chart of both nozzles (original or modified) is made and it is discussed the effective parameters with the best results obtained for the inclusions removal.

2.5. Image Processing

To quantify the inclusions that were trapped in the layer of lubricant powder, analysis and image processing was carried out, under graphical programming environment, LabVIEW™. One of the most important utilities of the NI-IMAQ software is the identification of the coordinates of physical elements of different shapes, this allows to calculate the coordinates of moving objects in time, which facilitates calculations of the speed, position, acceleration, among others. The tools that are available in the software package are easy to implement, and the best of it is to allow greater control of the dynamic processes.

3. Results and Discussion

The experimental results are analyzed in two stages; the analysis of the vibration measurements, and the inclusions removal in order to correlate the signals obtained with accelerometer and the behavior on the inclusions in the continuous casting funnel type mold.

3.1. First Part: Vibrations Measurements

Some trials were made in the water model in order to evaluate the usefulness and sensitivity of the accelerometer and see if this could be used to measure the energy levels of the metal stirring within the continuous casting mold and correlate it with the oscillation of the jets coming from the nozzle ports.

Based on the results of the physical simulation, it was possible to analyze and determine that there is a directly proportional relationship between the increases in the intensity of the vibrations of the mold, measured with an accelerometer, device that measures proper acceleration (g force) and the increases of the continuous casting speed. This relationship is shown in Fig. 3. These results were obtained through the continuous monitoring of each of the volumetric flows, showed in this figure at 210 s time. Then this data were normalized and integrated mathematically (from point 1 to 4).

From the information obtained from the mathematical modeling phase, a comparison is made of how the fluid behaves in the walls of the model in Fig. 4. As it is expected for higher casting speed, there is an increased flow velocity in the mold walls that it can be translated as a greater intensity of the vibrations that occurs due to greater energy dissipation in the model.

Taking as a reference points 1, 2, 3 and 4, and as it was mentioned before, different levels of vibration for the three different casting speeds were obtained with regards to the digitization of accelerometer signals. In Figs. 5 and 6 the accelerometer signals are shown, corresponding to the four selected points in the mold.

As it can be seen, at the higher casting speed the higher vibration values are obtained and this refers to the higher
Another important aspect to analyze is that the logic shows that at the point 1, in Fig. 5, one would expect to have the most intense signal vibrations (area where the jet hits directly) and what is seen is the formation of a zone of very low speed and "cushion", where the vectors of the fluid actually do not collide. The jet takes two paths: the upper and lower recirculation; in this latter part of the flow its speed increases rather than dissipate due to the mixing scheme that is presented in order to maintain the mechanical equilibrium.

Analyzing now the intensity of the vibrations at point 4 this is higher than the one in point 1, since the point 4 is positioned in a region of higher velocity on the thin wall of the mold. Since this is in an area where the speed of the circulation changes in direction toward the area where the nozzle is located, decreasing with this the speed of the fluid as well the intensity of the vibrations. While point 1 is below or slightly above the impact zone of the fluid jet coming from the nozzle ports, which is another area with almost no speed but with slight detected vibrations as it was previously mentioned. The cause of the above mentioned are the oscillating jets, which affects the intensity of the vibrations at the other monitoring points.

Moreover, the Point 2 in Fig. 6, which is positioned 34 cm above the jet impact area with the thin wall (Point 1), where the fluid begins to pick up speed in his ascent to the meniscus, this due to the transfer of movement caused by the jets from the nozzle ports thus showing that although the speed is slightly lower than in Item 3 (Fig. 4), it is not for the dissipation of turbulent kinetic energy, therefore, the intensity of the vibrations will be higher for point 2 than for the point 3 due to the fact that there is more fluid friction on the thin wall of the mold, which is causing further washing of the crust of therecently solidified steel and increasing the risk of a possible breakup thread and therefore presents the highest speed in the recirculation of fluid to the meniscus area.

However, to ensure that the results shown in Figs 5 and 6 are reliable and that the intensity of the vibrations, measured on the thin wall in the physical model of the mold, keeps a direct relationship with the behavior of the jets from this nozzle ports, the dissipation of the turbulent kinetic energy was measured with the use of the mathematical modeling. Three graphs was done, whose results are shown in Figs. 7, 8 and 9 for three different times (190 s, 200 s and 210 s), at three different casting speeds 4, 5 and 6 m/min and for both scales used in both; the physical simulation, superior part, as in the mathematical simulation, bottom part (Table 1).

Analyzing the Figs. 7, 8 and 9, it can be seen that the closer to the end of the mold spot (ME) is point 1 where it can be clearly seen that the turbulent dissipation (b) at this point is very close to zero because there is no direct friction of the fluid with the thin wall of the mold rather this area being a stagnant fluid region. The turbulent dissipation rate was measured in a central plane at 5 mmm from the thin wall mold in the mathematical model. Now, we did observe that the intensity of the vibrations (a), like dissipation, shows little activity in this area although it slightly increases with the increase in the casting speed, something
that is logical, according to Fig. 3.

Analyzing now point 2 can be clearly seen that both the dissipation of turbulent kinetic energy and the intensity of the vibrations is higher in this area, which is an indication that it is in this area where there is greater friction, of the fluid with the thin wall of the mold, and therefore a greater washing of the freshly solidified steel crust, gradually reduced in points 3 and 4.

Thus being shown that the proposed transducer, accelerometer, not only can be used to detect changes in the flow pattern, which is transduced in the detection of the oscillations created by the jets from the nozzle ports and that impacts the thin steel layer solidified, besides fluctuations in the steel-slag interface and in the prevention and correction of possible thread breakage. This might lead to a higher productivity of the continuous casting process and improved control of it. Also this can be taken as the start point to proof the relationship that exists between the removals of inclusions and the intensity of vibrations, measured with the accelerometer.

3.1.1. Correlation between the Vibrations Levels with the Removal of Inclusions

In the figures, from 5 to 9, the ratio of the vibration levels is shown at three different casting speeds in four different points. It is clear and determinant that the casting speed at 6 m/min and a depth of 34 cm nozzle, the mold shows the highest level of vibrations. For each of the signals it was carried out a polynomial fit, as is shown in Figs. 5 and 6.

This shows that a higher dynamic activity caused by high casting speeds, the accelerometer translates it as high levels of vibration within the continuous casting mold, which is reflected in increased disposal or removal of inclusions. This shows that the accelerometer is a device capable of detecting, through its processed digital signal, the energy generated in the mold of continuous casting of thin slab and it can be correlated with the elimination or removal of inclusions in it.


In Fig. 10(a) the inclusions can be observed in the nozzle port at a casting speed of 5 m/min at a time of 1.5 seconds, and in Fig. 10(b) the inclusions are observed at a time of 4 seconds under the same conditions. In Fig. 10 it is also observed that many of the inclusions are entering a low speed region, which is due to a change of area, by the conical shape of the mold. This gives an opportunity to the inclusions, which remain in this zone, to be floated or worse, the chance to be reinserted to the fluid dynamic pattern. It is also noted that they can be torn many particles of the slag layer due to the drag forces that cause the vortices, which are induced by collisions of flows with the nozzle, leading to changes in velocity and pressure.

For experiments with casting speeds of 4, 5 and 6 m/min to a depth of 22 cm nozzle, some of the results are shown in Fig. 11 as percentage of removal of inclusions. Importantly, the results of the physical simulation it was performed only for the original nozzle at two depths of the immersion
nozzle. In Fig. 11 it can be seen, as it was mentioned before; at higher casting speeds, greater the percentage removal of inclusions is obtained. And this can be explained because at high casting speeds, the drag force due to the fluid recirculation, allows to embed a large amount of inclusions in the slag layer, a fact that is also related to the shorter residence time of the particles in the mold.

Similarly in Fig. 12 (physical model) it can be seen that a casting speed of 6 m/min there is an increase in the removal of inclusions. To a casting speed of 4 m/min there is a notoriously slow elimination of inclusions, mainly because they are sent directly within the mold and they do not have enough speed to reach the surface, i.e. to the slag layer.

Regarding the design of the nozzle, in Fig. 13 (mathematical model), it can be seen that the redesigned nozzle can remove, on average, up to 1.6 times more inclusions than the original nozzle at a depth of 22 cm. Notice that the removal rate increases relative to the increase in particle size. This is mainly due to the fact that the larger particles reach the velocity of flotation easier, according to Stokes law. This is also based on the fact that the increase of the casting speed, enhances the dragging speed, and then the particles are carried to the solidification front or to the metal-slag interface, where they are trapped.

With the nozzle at 34 cm depth the same behavior is observed, i.e., higher casting speeds results in greater removal of inclusions, but not in the same proportion and within the same quantities, in average less than 11.5 times that the one obtained with the nozzle at 22 cm depth. In Fig. 14 (mathematical model) it is observed that the modified nozzle removes more inclusions than the original, but to a much lesser extent, on average 1.1 times more. This is mainly due to the fact that being the nozzle deeper, the inclusions tend to immediately go to the bottom of the slab, and only some are trapped in the upstream flows, providing an opportunity for some inclusions to be trapped in the slag/metal interface.

In conclusion it can be seen that there is a very good correlation between the results of physical simulation, Figs. 11 and 12 with those obtained with the mathematical simulation, Figs. 13 and 14 at a casting speed of 6 m/min.
4. Conclusions

(1) The mathematical and physical simulations as well as the vibration analysis have been proved to be very useful tools that can provide real and measurable values of the amount of energy in the mold and could be an indicative of how the inclusions are eliminated.

(2) For analysis of the behavior of the inclusions, it was observed that the tendency of the particles is being forced to the bottom of the model when the casting speed is increased, because of the jet oscillation of the nozzle, causing that the interface (slag-metal) fluctuate in an almost constant basis. This is consistent with what had been already used in mathematical simulations,\(^1\) in the sense that in the area near the nozzle a higher concentration of particles is presented, which is due to low speed present in the zone.

(3) The geometry of the original nozzle has provided the basis to improve and make appropriate changes for the proposed one, to improve the entrainment of inclusions, and to enhance the flow pattern, reducing the oscillation of the jets from the nozzle ports and thus causing less fluctuation of the surface, coupled with the improvement of the flow pattern inside the mold. Consequently it results in greater removal of inclusions in the slag layer (layer of lubricant powder).

(4) It has been found that the casting speed and the particle size were very important factors for the removal of inclusions.

(5) The increase in the casting speed generates more drag force and therefore greater percentage in the removal of inclusions, being dragged the fundamental force in the particle removal.

(6) It was found that the accelerometer could be a transducer capable of correlate the intensity of the vibrations with the behavior of inclusions in the continuous casting mold. Showing that at higher intensity of the vibration, the higher amount of inclusions could be eliminated.

(7) It also was found that the accelerometer could be used as a device to detect and prevent possible yarn breakage in the thin slab continuous casting machine.

Nomenclature

\( R_{\text{inc},m} \): Model inclusion radius (m)
\( R_{\text{inc},p} \): Prototype inclusion radius (m)
\( \lambda \): Scale factor
\( \rho_{\text{inc},m} \): Density model inclusion (kg/m\(^3\))
\( \rho_{\text{inc},p} \): Density prototype inclusion (kg/m\(^3\))
\( \rho_s \): Steel density (kg/m\(^3\))
\( \rho_w \): Water density (kg/m\(^3\))
\( g \): g force, proper acceleration (mV/s, transducer resolution)

REFERENCES