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REFRACTORY DESIGN AND PROCESS OPTIMIZATION IN TATA CSP® CASTER AT TATA INDIA

Abstract:
Technical solutions and design optimizations for better quality, increased productivity and yield improvement have been continuously introduced and implemented in Tata Steel thin slab plant located in Jamshedpur – India to further improve competitive edge in the current steel market.

Extensive advanced computer simulations and physical simulations have been conducted to determine the different parameters characterizing both tundish and mold flow. Reduction of dead and cold steel volume, improved inclusion floatation and turbulence reduction in the impact region have been obtained after optimizing the internal tundish geometry.

With the new tundish internal geometry, the tundish weight has been reduced by approximately 4 tons. Addition of tundish gas bubbling device aka TGD led to a reduction of process issues.

The new Sub-Entry Nozzle is used to produce stable meniscus flow and optimal mold temperature distribution for flow rate exceeding 4T/min without the need of electromagnetic brakes

Keywords: Thin Slab SEN, CSP®, YES tundish, tundish skull, TGD, SEN design

Introduction:
The CSP® LD3 caster at Tata Steel, Jamshedpur is the fourth CSP® shop in India with an annual production capacity exceeding 2.4MT per annum, producing strip steel up to 1680mm wide. The steel grades produced are high value added grades such as silicon grades, line pipe and dual phase steel.

Tata technical team and Vesuvius along with their supporting teams¹ are continuously optimizing the design of both the tundish geometry and the sub-entry nozzle to improve mold flow stability at high casting speed and subsequently improve tundish yield.

Background:
The authors conducted many water model trials using dynamic similarity (Froude number
equivalence between model and real system\(^2\) and then several numerical simulations to determine and optimize the flow performance of the studied tundish. Then design improvement along with tundish furniture addition have been considered.

A tundish prototype, of one third scale was used for the physical simulation. The tundish current configuration includes a Turbostop\(^\text{TM}\) impact pad that controls the flow coming from the ladle shroud considered relatively vertical, Fig.1.

![Fig.1: 1/3rd Scale tundish prototype of Tata LD3 tundish](image1.png)

**Water modelling experiments and results:**

The dynamic similarity between the prototype and the real plant conditions were maintained by keeping Froude’s number constant.

![Fig.2: Dye injection in water model Tata LD3 tundish](image2.png)

The dead zones, i.e, the lowest velocity and often the lowest temperature regions, are located inside the circles in Figure 2, along the bottom floor and around the flow regulating stopper. The liquid present in these regions can interact chemically (re-oxidation) and thermally with the tundish refractory lining.

These dead zones can be replaced by refractory in a profiled tundish aka YES (Yield Enhanced System) tundish\(^3\) or can be mixed through inert gas injection.

The Tundish Gas Diffusor or TGD is a bubbling barrier that is used to provide the required mixing behavior. The position of the TGD will be determined by water model experiments to optimize the mixing behavior for given gas flow rate. The gas flow rate has been maintained at around 25 LPM.

![Fig.3: Flow comparison for different positions of TGD as compared with the current tundish (a), 750 mm (b), 1350 mm (c) and 2000 mm from stopper. Pictures are taken when dye reaches outlet.](image3.png)

![Fig 4.: Concentration curve comparison for different TGD positions as compared with the current Tundish configuration](image4.png)
Fig 4. shows the residence time distribution curves of liquid steel inside tundish at different positions of Tundish Gas Diffuser and its comparison without argon purging (Dam only).

With argon purging, the peak concentration is shifted towards the theoretical average residence time indicating better plug volume and enhanced mixing volume.

The dead volume is reduced wherever the TGD is placed, see Fig.5. The best TGD position is at 750 mm from the stopper.

As previously stated by D. Sheng and L. Jonsson⁴, most of researchers are supposing that the forced convection is dominant in the tundish flow behavior and that the density and the viscosity variations of the liquid steel are so small that the free convection (thermal driven flow) can be ignored.

That means that the influence of liquid steel temperature variations (due to heat loss to the atmosphere by conduction through the refractory walls, by radiation through the insulating meniscus) and temperature inhomogeneity (such as thermal stratification) of the liquid steel discharged from the ladle into the tundish, is ignored applying standard (isothermal) water model tests.

Using a non-isothermal water thermal conditions highlights the effect of temperature driven buoyancy forces on the overall flow behavior inside the tundish.

In order to simulate the Non-ISO thermal conditions, a dimensionless number called Tundish Richardson is considered as a similarity criterion to determine the convection pattern in tundish system and in the model⁴. The requirements of dynamic similarity by keeping the Froude number and Tundish Richardson number constant between the prototype and the model is satisfied with:

\[ Fr = \frac{u}{\sqrt{gL}}, \quad Tu = \frac{gL\beta\Delta T}{u^2} \]

And \(u\) – fluid velocity, \(L\) - characteristic length, \(\beta\) - thermal expansion coefficient, \(g\) - gravity, \(\Delta T\) – thermal gradient.

For water and steel:
\[ \beta_{\text{water}}/\beta_{\text{steel}} = 3.48 \times 10^{-4} / 3.9 \times 10^{-4} = 0.89 \]

In a \(1/3\) rd scale tundish water model, if the water temperature at the inlet (ladle shroud or exit of ladle) is 10°C hotter or colder than the water in the tundish, that will correspond to around 25°C in steel plant.

At the end of a heat, corresponding in general to more than 50 minutes of draining (particularly in absence of a ladle lid), the liquid steel can be cold, in fact colder than the liquid steel present inside the tundish.

Hotter or colder water is poured into the tundish filled with room temperature water. The hotter
(lower density and lower viscosity) water flows over the cooler and heavier water. The supernatant liquid can flow over the Turbostop™ impact pad along the meniscus and over the dam. This circulation flow pattern is promoting floatation of incoming inclusions present in the ladle or formed in the tundish pouring region but the dead volume generally located along the tundish floor (blue curve) can increase in size.

Using the non-isothermal modelling, different positions of the TGD were compared with dam alone configuration to determine the best position of TGD for thermal homogenization.

Fig 6: Flow comparison for HIC (=Hot into Cold) for TGD as compared with the current Tundish (a), 750 mm (b), from stopper when the dye reaches the tundish outlet.

Without TGD, the incoming hot fluid stream, flows over the Turbostop™ impact pad along the meniscus and short circuits towards the outlet. A large dead volume (high contact/residence time with the tundish lining) is generated along the tundish bottom, see Fig.6.

Fig 7 shows the residence time distribution of liquid steel inside tundish with and without Tundish Gas Diffuser and its comparison without argon purging under hot steel into cold condition, corresponding in general to the first minutes after ladle opening.

Fig 7: Non ISO-Thermal C-Curve Comparison for HIC for different positions of TGD as compared with the current Tundish

TGD helps to reduce the drastic effects of the temperature driven buoyancy by promoting mixing inside the tundish. Then the MRT is increased by up to 28% (from 35s to 45s in water) by preventing short circuiting.

When cold steel flows, like during ladle final draining stage, the heavier incoming cold stream flows along the tundish bottom and pushes towards the outlet the high residence time cold steel present in the dead zones.

This condition creates large dead volume near the tundish meniscus around the stopper, Fig 8a).

If this cold steel freezes, a metal/slag ring is observed around the refractory part and may disturb flow regulation by adding drag forces during the vertical motion of the flow regulating stopper.

Fig 8: Flow comparison for CIH for different positions of TGD as compared with the current Tundish (a), 750 mm (b), from stopper at MRT.
Fig 9: Non ISO-Thermal C-Curve Comparison for CIH for different positions of TGD as compared with the current Tundish

Based on the entire water model study, the TGD at 750 mm from stopper gives a better performance and a predictable behavior in terms of dispersed Plug volume and a reduction in dead volume for both iso-thermal and non-iso-thermal condition.

The authors also designed an optimized tundish profile referred as the Yield Enhancement System tundish aka YES tundish to reduce the steel skull size left at the end of the casting sequence. This tundish design features side vertical walls described as side rails resulting in a profile that is narrower at the bottom, see Figure 10. This allows additional benefits to be realized in terms of improved yield at grade transition, extended tundish life and a reduction of the amount of working lining.

To prevent the negative impact from tundish volume reduction with the YES tundish, a Turbostop™ impact pad is used. The reduction in tundish width (or side rails) is starting below the critical level reached during ladle exchange or during grade transition. The level change between the operating level and the level at which the new ladle is opened is identical to for the conventional tundish inside which the new profile will be implemented.

Figure 10: A view of a profile inside a YES tundish with the side rails and a stepped floor in Tata LD3.

This volume reduction in the lower tundish region contributes to enhanced steel cleanliness by removing high contact residence time (=re-oxidized) steel volume, to better yield with smaller tundish skulls, to tundish refractory life increase by improving skull dumps.

The new tundish profile allows reduction of the tundish skull by approximately 4.5T if closing at same drain level as current practice, i.e 450mm.

Fig. 11: Tundish skull size for the current (blue) and the new YES tundish profile (red)

With the YES tundish (5 tundishes converted) the average tundish skull weight is around 8.5T Fig.11
or only 1T less than the current tundish shape due to early sequence termination related to various factors.

**STEEL FLOW CONTROL REFRACTORY DESIGN OPTIMISATION:**

The authors are continuously evaluating and modifying the mold flow performance produced by the Sub-Entry Nozzle referred to as R3. This SEN design has been optimized through numerous computer simulations.

The open-source CFD code, OpenFoam® software and the commercial pre-processor GAMBIT were used in this study. This solver was used to calculate the Reynolds-Averaged Navier-Stokes equations with turbulent closure provided by the $k-\omega$ SST model. The standard wall function treatment was applied at the walls of the tundish.

Design modifications have been implemented to the R3 SEN to develop the longer life R3Boxy SEN and to introduce recently a later generation of high performance nozzle for wide molds at high throughputs greater than 4T/min without the need of an electromagnetic brake.

Through multiphase – VOF- simulations, the maximum throughput achieved for the R3 to prevent mold powder entrapment is reached between 3.5T/min and 3.8T/min depending on the SEN submergence, mold width and mold powder properties, see Fig.12 and Fig.13.

![Fig. 12: Meniscus profile – R3 SEN at 3.5T/min in 1550mm wide mold](image)

![Fig. 13: Mold powder surface area in contact with R3 SEN refractory at 3, 3.5 and 4T/min in 1550mm wide mold.](image)

Over 3.8T/min in Tata LD3 casting conditions, mold powder can be entrained as simulated in Fig.14 and if the entrained mold powder is coating the refractory below the slag line erosion resistant material, then severe undercutting occurs.

![Fig. 14: Example of mold powder entrapment when the meniscus velocity is too high.](image)

The R3Boxy was designed to reduce the sub-meniscus velocity, to improve the flow symmetry, to reduce flow instabilities between the port exiting jets and to reduce the formation of vortices in the funnel region and particularly between the
mold copper and the nozzle, see Figures 15 and 16.

The meniscus is more deformed than what has been calculated for the R3 at 3.5T/min and mold powder can be entrained near the funnel entrance.

The erosion of the submerged refractory walls is limited for R3Boxy SEN in the 1680mm wide section, during 15 heats, for a total duration of 10h50min, see Fig.16. The total tonnage cast was 2450T thus corresponding to an average casting speed 3.9T/m in of over the entire sequence.

Over 4T/min, mold powder is entrained and coats the refractory surface below the erosion resistant material. This leads to undesired erosion thus limits the usage time.

However, to consistently cast over 4T/min, in wider mold sections without the need of an electromagnetic brake, further design enhancements are required to limit mold powder entrainment.

With the optimized SEN geometry, mold powder entrainment along the outside refractory surface below the zirconia sleeve, Fig. 17 and 18, is comparable to the R3 at 3.5T/min condition, for which the refractory performance is satisfying.

A new high throughput SEN design has been introduced to produce a stable meniscus flow while casting slabs widths greater than 1500mm at throughputs exceeding 4T/m in in average. This newer SEN design reduces the port exit jet velocity and forces the flow in the funnel region to decelerate around the SEN outer geometry.
Consequently, the vortex formation related to flow competition in the funnel region is therefore reduced so as the mold powder entrapment.

This new SEN design allows stable casting at throughputs around 4T/min, Fig.19.

As simulated, see Fig 17, the hot metal is uniformly distributed along the meniscus providing optimal mold powder melting, Fig.20.

Fig. 19: Average throughput per heat on a 27 heats sequence with new High Throughput SEN.

The evenly distributed erosion is localized within the slag line sleeve, Fig.21.

Tata LD3 is using the 3 SEN designs for different throughput ranges. The R3 produces a mold level standard deviation around 0.5mm for throughput up to 3T/min. The mold level standard deviation is around 0.6mm for the R3 Boxy, see Fig.22. For the new high throughput SEN, the mold level standard deviation is around 0.65mm, Fig.23.

Fig.20: New High throughput SEN during casting.

Fig.21: Pictures after casting of new High Throughput SEN

Fig.22: Mold level standard deviation for R3 and R3 Boxy in function of throughput.
Both Fig.22 and Fig.23 are highlighting the variations of mold level standard deviation regardless of throughput. Thus it is important to determine the origin of these higher values in order to improve mold level control and to prevent surface quality defect formation related to these fluctuations as seen in Fig.23.

The steel temperature is continuously measured near the tundish outlet by using an Accurod™ stopper.

In the rectangle in Fig.24 and Fig.25, the mold level fluctuates after a strong temperature decrease followed by a hot ladle. The mold level standard deviation exceeds 0.65mm.

As observed in water model the dead volume and the cold steel residing along the tundish floor are pushed towards the outlet. It is expected that during a heat the temperature is decreasing steadily. But if the temperature drops quicker colder steel is reaching the tundish outlet, coming either from the ladle or from the tundish floor.

The “Cold into Hot” condition followed by “Hot into Cold” case seems to be associated to severe mold level fluctuations (>0.7mm) as seen in Fig.29.

The use of both the YES tundish and the TGD allow time reduction of these unstable periods from 20-25minutes with high mold level standard deviation values down to less than 15minutes except during the first ladle change, see Fig.26.
temperature variations and mold level standard deviation) during a sequence with HTP SEN, TGD and YES tundish.

Future work will certainly be focused on improving the thermal homogeneity of the liquid steel inside the ladle and a better tundish temperature homogenization with a better use of the TGD.

From extensive analysis of the casting parameters, it is recommended to avoid:

- strong throughput decrease particularly towards the end of the ladle draining,
- strong throughput increase when pouring a new hot ladle,
- large variations of tundish weight during the ladle draining.

CONCLUSIONS

In order to improve the overall tundish flow, a new profile and a bubbling barrier have been introduced to the Tata LD3 tundish.

The influence of the ladle steel temperature on the tundish flow has been investigated. The profiled tundish and the gas diffusor are design to better control the tundish flow.

In addition a new SEN has been developed to cast over 4T/min in wide slabs.

The SEN designs used in Tata LD3 are promoting stable meniscus flow with mold level standard deviations around 0.6mm.

Further analysis of the casting parameters have highlighted the importance of steel temperature prior, during and shortly after the ladle change.

During that period, mold level instabilities are observed.

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References:


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