“Vacuum Shroud (VS)”-A Green Flow Control Device (FCD) towards Replacement of “Turbo Stop” In Tundish Metallurgy

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Abstract In 21st century due to global market steelmakers are facing tough competition to sell product and for that reason stringent quality steel is required to manufacture. As tundish is an important buffer before the steel cast to semifinished product so it is the aim of the metallurgist over the last three decades to enhance the performance of this reactor. In this regard slag eye formation, slag metal emulsifications, turbulence during metal transfer operation at the time of ladle changing period and inclusions generations from re-oxidation have adverse effects towards production of high purity liquid steel. To combat these phenomena researchers have tried to develop different shrouds and impact pads to control the turbulence within the steel melt during steady and unsteady state operations. But no technology is able to reach to the ultimate success. In the current context a new concept has been developed called “Vacuum Shroud (VS)” which studied numerically by using ANSYS FLUENT software to explore the effect of currently innovative flow control device in comparison with others previously developed technology towards improvement of the tundish performance. It is found that the novel device is highly capable to replace turbostop and will reduce the mentioned problems forever.

Keywords: shroud, impact pad, slag eye, emulsifications, slag entrainment, inclusions, oxygen pick-up, tundish

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1. Introduction

Slag Eye & Emulsifications in tundish are critical problems generally observed in tundish and ladle, during flow of liquid steel from ladle to tundish and ladle purging phenomena respectively. Over the last three decades many researchers had tried to inhibit generation of slag eye as it promotes re-oxidation of liquid metal due to exposure of high temperature liquid steel at atmosphere and detrimental inclusions are created from re-oxidation which ultimately affect the quality of product and uncertain clogging of the submerged entry nozzle during pouring of steel in the mold which hinder production. This open eye basically formed in tundish system due to high turbulent fluid entrance in this metallurgical reactor during pouring period through shroud from ladle to this vessel. Not only slag eye formation and re-oxidation due to oxygen pick up, emulsification and contamination of liquid steel frequently happen in the integrated steel plant from high turbulence liquid steel during ladle change over period at tundish. At the end of pouring there is a high chance to entrainment of liquid or semi-solid slag to the vessel bath cause high turbulence within the tundish melt during slag floatation incorporate some slag metal emulsification and contamination to the liquid steel melt within the tundish which affect ultimate the product quality. Beside these

adverse effect sometimes blow-back phenomena dangerously affect the operator’s safety also [1]. Turbostop or impact pad initially developed to combat this slag eye generation and reduce turbulence in tundish melt. The details flow patterns by using turbo stop have been investigated early by some researchers [2]. But it is little bit effective to control these phenomena. So certainly it is required for the metallurgist to get an ultimate solution of these problems. Several researchers have developed different shroud configurations like trumpet shaped shroud [3], dissipative shroud [4], advanced pouring box [5], swirling ladle shroud [6], bending nozzle [7], velocity interrupted shroud [8] etc to inhibit to happen these phenomena. But still these detrimental effects are occurring in tundish during daily operation time to some extent.

Figure 1 (a) is the observation of slag eye during actual plant scale operation at continuous casting process in tundish [9]. Figure 1 (b) shows the contaminations of liquid steel from oxygen pick up at different stage of processes from ladle to tundish transfer of high temperature metal. The figure exhibit 10% oxygen pick up takes place during tapping operations at ladle from converter, 15% re-oxidation occurs at the stage of alloying addition and ladle purging, 5% contribution comes from ladle slag and tundish lining, most important during ladle stream flow to tundish creates 40% contamination to liquid steel due to formation of slag eye, emulsifications and inclusions generations and

finally thinning of tundish slag from turbulence contribute 30% of re-oxidation procedure [10]. So it is readily understandable that huge quantity liquid steel contaminated in the tundish during ladle to tundish transfer of liquid metal which adversely affect not only the product quality and sometimes cause high amount metal down gradation due to aluminum silicon reversal within the melt from tundish flux as an occurrence of

uninterrupted emulsifications from turbulence. It is observed by the researchers that control of ladle stream flow important for generation of stable slag eye and high speed flow produce emulsified slag eye due to metal fluctuation from turbulence [11]. Laboratory experiments explore that exposed eye developed from argon shrouding in the tundish shroud nozzle during melt transfer from ladle to tundish vessel [12].

Figure 1. (a) Photographic image of slag eye at Industrial Operation (Reprinted from [9].) (b) Contribution of different abnormalities on contamination of steel (Reprinted from [10].)

So from the above mentioned literature it is found that to control turbulence and emulsification within tundish reactor, it is desperately require to develop some

technology which will be highly effective to minimize turbulence and emulsification in this metallurgical vessel to maintain quality of the product on sustained basis and

simultaneously reduce the loss of plant from down gradation of the semi finished product to improve the yield of the plant as a result of plant performance will be enhanced which indirectly related to the profit of the manufacturer. From 1975 to 1993 different impact pads and technology has been patented by several researchers like Neuhaus, Ishiyama et al, Schmidt, Vo Thanh et al, Soofi etc to decrease turbulent within the tundish from inlet stream [13,14,15,16,17]. In November 1993 Karl J. Saylor an inventor of CCPI, Inc. of the United States of America make a patent of turbulence inhibiting impact pad which help successfully to reduce the turbulent certain [18]. The tundish contain the following components tundish , inner lining , outlet block , molten bath , ladle shroud , tundish impact pad and upward stream. Still today this impact pad use widely in the continuous casting plant as a velocity breaker. After using this impact pad and conventional shroud also emulsifications during ladle change over period and slag eye formation are common phenomenon in tundish metallurgy. So even today also researchers and metallurgists are engaged to develop different shroud configurations as well as designing of typical turbostop to get the ultimate solution of this detrimental occurrence.

In September 2010 a technology has been patented in United States by some inventors named Gerald Hohenbichler, Gerald Eckerstorfer and Markus Brummayer of Voest-Alpine Industrieanlagenbau GmbH & Co. of Austria to inhibit these phenomena [19]. It is observed from the new invention that the shroud is fully submerged in the melt and the slag eye has been covered by side baffle fill with inert atmosphere through argon supply within the covered baffle by externally connected shielding gas line and it is mandatory for this process to check such that the baffle must be submerged condition slightly below the top surface of the liquid steel during ladle change over period. The arrangement contains melt vessel, shroud, tundish, slag layer, cover surrounding shroud, shielding gas line and turbostop. This technology will help to produce high quality casting product by aggravate the decay of fluid motion in the tundish during unsteady state operation and will help to achieve quasi steady state quickly as the invention demand. The present invention and study is a break through technological concept to reduce the aforementioned draw backs of tundish operation and will help to enhance the yield and product quality on a sustainability basis.

2. “Vacuum Shroud”-A Novel Technological Concept

It is mentioned in the literature that significant efforts have been performed by several researchers in collaboration with industry and academics over the last four decades to enhance the performance of this buffer reactor (Tundish) between ladle and last metallurgical reactor mold of continuous casting [20,21]. In this regard fluid flow takes a major role to increase the yield and quality of the cast product and the detailed understanding of the fluid flow, multiphase flow helped us tremendously to make new design of the equipment and develop new innovative processes towards more control over the

existing processes and simultaneously minimization to produce defect free semi finished product [22]. To achieve desired stable operation in tundish several researches have been devoted to change the design of the shroud and impact pad to control the slag eye formation, emulsification from turbulence, re-oxidation by oxygen pick up, slag entrainment during ladle draining period at the end of one heat casting and slag emulsification at the entering of another new heat during ladle change over period. Not only conventional shroud and turbostop as seen from the Figure 2 (a), some researchers have tried to compare the effect of other flow control device like baffles and dams incorporation with impact pad to control the flow pattern in tundish in comparison to bare tundish as well [23]. Dissipative ladle shroud shown in the diagram Figure 2 (b) is a relatively new technology recently developed by few metallurgists to avoid turbulent related problems in the so called metallurgical vessel tundish and physical modeling, mathematical modeling as well as particle image velocimetry have been employed to see the insight and performance of this new device which have been compared to the performance of commonly used conventional shroud, as a results shows sufficient open eye formation, slag emulsification generation, air entrapment for both cases during ladle change over period [4,7,24]. Long nozzle with bell type shroud and trumpet shaped shroud as embodied in Figure 2 (c) have been used by few steelmaking industry to decrease re-oxidation and nucleation of detrimental macro inclusions [3,9]. Swirling ladle shroud a new generation flow control device was developed by some researchers as observed from Figure 2(d) where recirculation flow was introduced in three intermediate chambers along the length of the nozzle by rotating blade [25,26]. This technology is successful to some extent to decrease the earlier stated problems but it is difficult to apply in actual high temperature plant operation due its manufacturing difficulties. So in the current study it is not numerically simulated. Figure 2(e) is bending nozzle basically apply in centrifugal flow tundish which has limited application and high erosion rate of nozzle [7,27]. So it is not discussed in current study. Different shapes impact pads were studied but advanced pouring box as shown in Figure 2(f) have successfully replaced all developments of turbo stop which contain small holes at the wall of the impact pad [5,28]. But still now all these developments have certain limitations and uncertainty to make a stable flow within tundish. So it is desperately desired by the steelmaker to develop a new sustainable breakthrough long lasting technology. In current study such an innovative technology has been conceptualized which contain a partial submergence of inner nozzle covered by a long submerged vacuum chamber as depicted in the Figure 2 (g). During operation due to vacuum the outer nozzle will be partially filled by liquid steel and through partially submerged inner nozzle ladle stream flow will pass to the tundish. Due to its novelty a new name has been proposed for this device – “**Vacuum Shroud**”. In present study the effectiveness of this device has been compared numerically with other previously developed technology by ANSYS Fluent simulation software which is currently available in the institute and most importantly for minimization of turbulence in tundish metallurgical reactor.

Figure 2. (a), (b), (c), (d), (e), (f) Schematic diagram of different shroud and impact pad combinations developed last three decades (Reprinted from [3,4,5,6,7].) (g) Vacuum Shroud with full scale dimensions

3. Mathematical Model and Equations are Used in the Present Study

• Mass conservation or Continuity equation

For 2D axisymmetric geometries, the continuity equation is as follows in equation (1):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho V_X)}{\partial X} + \frac{\partial(\rho V_r)}{\partial r} + \frac{\rho V_r}{r} = S_m \quad [29] \quad (1)$$

X – Axial coordinate, r- Radial coordinate, V_X – Axial velocity and V_r – Radial velocity and S_m – Source of mass addition from dispersed second phase to continuous phase respectively.

• Momentum conservation equations

For 2D axisymmetric geometries, the axial and radial momentum conservation equations are as described below in equations (2) and (3):

$$\begin{aligned} & \frac{\partial(\rho V_X)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho V_X V_X)}{\partial X} + \frac{1}{r} \frac{\partial(r \rho V_r V_X)}{\partial r} \\ &= \frac{\partial \rho}{\partial X} + \frac{1}{r} \frac{\partial}{\partial X} \left[r \mu \left(2 \frac{\partial V_X}{\partial X} - \frac{2}{3} (\nabla \cdot \vec{V}) \right) \right] \\ &+ \frac{1}{r} \frac{\partial}{\partial r} \left[r \mu \left(\frac{\partial V_X}{\partial r} - \frac{\partial V_r}{\partial X} \right) \right] + F_X \end{aligned} \quad [29] \quad (2)$$

$$\begin{aligned}
& \frac{\partial(\rho V_r)}{\partial t} + \frac{1}{r} \frac{\partial(r \rho V_X V_r)}{\partial X} + \frac{1}{r} \frac{\partial(r \rho V_r V_r)}{\partial r} \\
& = -\frac{\partial \rho}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left[r \mu \left(2 \frac{\partial V_r}{\partial r} - \frac{2}{3} (\nabla \cdot \vec{V}) \right) \right] \\
& + \frac{1}{r} \frac{\partial}{\partial X} \left[r \mu \left(\frac{\partial V_r}{V_X} + \frac{\partial V_X}{V_r} \right) \right] - 2 \mu \frac{V_r}{r^2} \\
& + \frac{2}{3} \frac{\mu}{r} (\nabla \cdot \vec{V}) + \rho \frac{V_z^2}{r} + F_r
\end{aligned} \quad [29](3)$$

Where $\nabla \cdot \vec{v} = \frac{\partial v_x}{\partial x} + \frac{\partial v_r}{\partial r} + \frac{v_r}{r}$ and V_z is the swirling velocity.

• Turbulence Model equations (standard k- ϵ)

Two equations (4) and (5) are solved for k and ϵ for turbulence model described below.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} \quad [29](4)$$

$$= \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k$$

$$\begin{aligned}
& \frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_i)}{\partial x_i} \\
& = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_e} \right) \frac{\partial \epsilon}{\partial x_j} \right] \quad [29](5)
\end{aligned}$$

$$+ C_{1e} \frac{\epsilon}{k} (G_k + C_{3e} G_b) - C_{2e} \rho \frac{\epsilon^2}{k} + S_e$$

G_k -Turbulence kinetic energy generation from mean velocity gradient, G_b - Generation of turbulence kinetic energy from buoyancy force, Y_M - Overall dissipation rate generated from fluctuating dilation of compressible fluid, C_{1e} , C_{2e} and C_{3e} are basically have constant value, σ_k and σ_e dictate the Prandtl number in case of turbulent flow condition for k and ϵ respectively, S_k and S_e user defined source components.

• VOF (Volume of fluid) Model equation

VOF (Volume of fluid) has developed based on time dependent solution and the phases are not interpenetrating. The tracking of the interface between phases in a particular mesh cell for q^{th} phase can be calculated by the following equations (6) and (7):-

$$\begin{aligned}
& \frac{1}{\rho_q} \left[\frac{\partial(\alpha_q \rho_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) \right] \\
& = S_{\alpha_q} + \sum_{p=1}^n (\dot{m}_{pq} - \dot{m}_{qp}) \quad [29](6)
\end{aligned}$$

$\dot{m}_{pq}$ & $\dot{m}_{qp}$ are the transfers of mass from **p phase** to **q phase** and vice versa respectively. The source component of the equation S_{α_q} treated as zero or any user defined constant. This volume fraction equation will not applicable for primary phase. The primary phase will be calculated based on the following equation. The VOF equation can be discretized by explicit and implicit schemes.

$$\sum_{q=1}^n \alpha_q = 1. \quad [29](7)$$

• Discrete Phase Model equations

In this model particle trajectory can be predicted by integrating force balance on the droplet or bubble particle in a lagrangian reference frame. The particle force balance equation can be written as follows explained in equations (8) (9) and (10):-

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x \quad [29](8)$$

F_x and $F_D(u-u_p)$ are the accelerating force per particle and drag force per particle respectively.

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re}{24} \quad [29](9)$$

F_x is basically additional force generate from pressure gradient which acting surrounding the particle can be expressed by the equation mentioned below:

$$F_x = \frac{1}{2} \frac{\rho}{\rho_p} \frac{d}{dt} (u - u_p). \quad [29](10)$$

For submicron particles from stokes law a different version of F_D equation is available which is given by the equation (11)

$$F_D = \frac{18\mu}{d_p^2 \rho_p C_C} \quad [29](11)$$

C_C is the Cunningham correction factor.

4. Results & Discussions

In the present study numerical simulations were applied by ANSYS FLUENT software using the above mentioned mathematical models and **equations (1-11)** like mass conservations equation, momentum conservation, standard k- ϵ turbulence model, multiphase volume of fluid model and particle transport discrete phase model equations. Full scale dimensions for different pouring nozzle were used and water, kerosene oil, air, argon were used as a simulating fluid as a representative of liquid steel and slag as the kinematic viscosity of the water and liquid steel are same respectively. 10 mm argon particles were injected for current study and the inclusions diameter was taken 50 μ m as this is the critical diameter of inclusion for generating sliver complaint in steel semi finished product [30]. The details dimensions and operating parameters are explained clearly in [Table 1](#). For all the cases 2D axi-symmetric model with standard k- ϵ model, multiphase VOF model, discrete phase particle tracking for inclusion and some cases argon injection from the velocity inlet were simulated whose details with time step size were embodied in the [Table 2](#). For newly developed shroud a small vacuum pressure in the range of 720-750 torr were maintained at the time of melt transfer from ladle to tundish bath.

Table 1. Tabulations of Physical Properties Used in Current Study

Sl. No.	Dimensions & Parameters	Value	Remarks
1	Length of the Shroud nozzle	1.2 meter	Full scale dimensions used present study
2	Diameter of Shroud Nozzle	0.09 meter	
3	Initial Velocity of pouring from velocity inlet	2 meter/sec	
4	Bath diameter and height	D = 1 meter, H = 0.5 meter	Turbostop diameter = 0.3 meter
5	Turbulent Kinetic Energy (k)	2	$k = \frac{1}{2} v^2$ [31]
6	Turbulent Dissipation rate (ε)	0.18	$\epsilon = \frac{C_\mu \times k^2}{v}$ [31]
7	Water (secondary phase)	Density-998.2 kg/m ³	Liquid steel represent water as kinematic viscosity same for both fluids
8	Kerosene oil (secondary phase)	Density-780 kg/m ³	Represent slag
9	Air (primary phase)	Density-1.225 kg/m ³	
10	Argon (secondary phase)	Density – 1.629 kg/m ³	Flow rate-20% volume fraction of water from velocity inlet
11	Inclusions (wood particles)	Diameter – 50 μm	Density-700 kg/m ³ , flow rate – 0.00453 kg/sec
12	Vacuum Used	Atmospheric pressure-760 torr, Pressure maintained Vacuum Chamber of Shroud 720-750 torr	This vacuum pressure maintained within the vacuum chamber of the shroud
13	Argon flow rate & Particle diameter used in DPM Calculation	0.0008 kg/sec, 0.01 m diameter argon bubble	Inclusion and argon particles both injected from velocity inlet

Table 2. Summary of Mathematical Models Used in Current Study

Sl. No.	Simulation Parameters	Short Descriptions
1	Model & Solver	2ddp (2-D double precision) Axisymmetric, 1 st order Implicit, Pressure based Unsteady
2	Boundary conditions	Velocity inlet, Pressure outlet, Wall, Exhaust fan, Axis
3	Viscosity	Standard k-ε, standard wall functions, C_μ -0.09, $C_{1\epsilon}$ -1.44, $C_{2\epsilon}$ -1.92, TKE Prandtl No-1 [32]
4	Volume of Fluid	Explicit, Courant No-0.25, Implicit body force
5	Discrete Phase Model (DPM)	Unsteady particle tracking with particle time step size 0.05 sec, spherical drag law, work pile algorithm, Discrete random work model, Random eddy life time
6	Time step size	0.2 sec per iteration
7	Control Solution	Pressure velocity coupling-SIMPLE, Discretization (Pressure-PRESTO, Momentum-1 st order upwind, Volume fraction- Geo-Reconstruct, Turbulent kinetic energy and dissipation – 1 st order upwind scheme)

Initially simulation study were done with 3 phases flow condition (water-oil-air) subjected to a plot of velocity contour at Figure 3 for different shroud configurations when from the velocity inlet the fluid is pouring at initial velocity of 2 meter per seconds to the bottom of the bath. It is observed from the figure that the fluid is impinging on the bath at higher velocity for conventional shroud [Figure 3 (a)] and advanced pouring box [Figure 3 (d)] followed by flows upward towards surface of bath fluid or slag phase. In case of trumpet shaped shroud [Figure 3 (b)] the water is falling on the turbostop at the bottom of the bath at comparatively slow rate. The fluid velocity alternately increasing and decreasing inside the dissipative nozzle [Figure 3 (c)] and finally pouring on the impact pad slightly lower rate as compared to conventional shroud. Figure 3 (e) and (f) shows gradual pouring condition of vacuum shroud (VS) where it is seen from the color contour plot that the water is hitting the bath bottom wall at a very slow velocity than the other different shroud and

impact pad configurations and for that reason the upward velocity also less which is an indication of less turbulence within the bath fluid during transfer procedure. Figure 3 (g) and (h) is the velocity magnitude plot along the nozzle from the velocity inlet to bottom of the bath and center of the bath to bath wall respectively. It supports the velocity contour plot results that for conventional shroud and advanced pouring box the velocity gradually increase upto the bottom of the bath and for other cases the velocity drops during hitting to the base of the bath as seen from Figure 3 (g). The upwards side stream velocity generate after impinging the water on the impact pad shows very high value for conventional shroud with turbostop and very low value observed from Figure 3 (h) for vacuum shroud (VS). Trumpet shaped shroud, advanced pouring box and dissipative shroud have intermediate value for side stream upward velocity which again indicate that vacuum shroud (VS) is superior to control turbulence than any other flow control device.

Figure 3. (a) to (f) Velocity contour plot

(g)

(h)

Figure 3. (g), (h) Graphical plots of velocity along vertical and horizontal directions respectively

The changes of static pressure along the nozzle up to the bottom plane of the bath and from center of the bath to the side wall of the bath plotted in the Figure 4 (a) and (b) respectively. It is generally observed from the figures that high pressure within the bath were created for conventional shroud and impact pad combinations and also for conventional shroud and advanced pouring box case. Lower static pressure as a whole for the bath generated only for vacuum shroud (VS) initial pouring and stable pouring conditions also as depicted in the Figure 4 (a) and (b). The static pressure within the nozzle varies

repeatedly due to dissipative action within the nozzle for dissipative shroud. For trumpet shaped shroud the static pressure at velocity inlet is substantial low and gradually increase before its falling to the turbostop of the bath as exhibited from Figure 4 (a). From the above velocity and static pressure contours and graph plots study it can be summarized that the new shroud is quiet capable to control turbulence and high erosion of the tundish refractory as compared to the other widely used technology in this area due to its suction effect on the incoming fluid to tundish.

(a)

(b)

Figure 4. (a) and (b) Graphical representations of static pressure along the nozzle vertically from bottom of the bath and horizontal direction from center to bath wall respectively

5. Slag Eye Study during Pouring

Stringent steel quality is required to maintain in the current global market to get sustainability. In this matter Tundish is an important metallurgical reactor where liquid steel quality can be improved by controlling the process using several flow control device. Slag eye or open eye is a common factor

regularly happens in ladle and tundish during gas purging and unstable operations also as mentioned in literature [33,34]. The quantifications of slag eye are important to judge the process performance. In this regard it is highly desirable to measure the open eye area or diameter to measure indirectly the oxygen pick up rate from the slag eye area and the amount heat can be loss through the exposed eye.

Figure 5. (a) to (f) Slag Eye Opening Areas during Initial Stage of Pouring of Liquid in the Bath

(g)

(h)

Figure 5. (g) Plot of density fluctuation at slag phase during primary stage of pouring (h) Statistical plot of slag eye area formed at this stage for all shroud configurations

Slag eye size during initial pouring condition as well as after reaching stable condition was evaluated numerically by FLUENT which has been exhibited in the Figure 5 [(a) to (h)] and Figure 6 [(a) to (h)]. It is observed from the Figure 5 multiphase contour and graph plot that for trumpet shaped and dissipative shrouds the slag eye size were large at the low metal bath level as large quantity initially entrapped nozzle gas evolution takes place for large diameter shroud. Conventional shroud with impact pad and conventional shroud with advanced pouring box produce similar results as same amount of entrapped nozzle gas evolved during ladle change over period. Figure 5 (e) shows the short vacuum period time for the

newly developed shroud when some amount of fluid will partially enter the shroud nozzle before pouring the liquid steel into the tundish bath. From Figure 5 (f) and (g-h) it is observed that practically negligible slag eye have chance to form during initial time of pouring for vacuum shroud (VS). Slag eye formed during stable condition due to upward impact of fluid to the slag phase (yellow color) which have been depicted in the Figure 6 [(a) to (h)] for different types shroud and impact pad configurations. It is observed from the Figure 6 [(a) – (f)] and statistical plots Figure 6 [(g) – (h)] that for conventional shroud with turbostop, dissipative shroud with turbostop the exposed eye area is large as compared to advanced pouring box,

trumpet shaped shroud with impact pad configurations as generations of high upward velocity after impact of high velocity fluid with the turbostop. In case of vacuum shroud shown in the Figure 6 (e) that at steady state operation in the tundish exposed eye free slag layer is observed due to

high rate of turbulence energy decay from the negative vacuum pressure. After reaching of certain height of fluid in the bath vacuum pressure were withdrawn which shows zero exposed slag eye for vacuum shroud due to large diameter outer nozzle as observed from Figure 6 (f).

Figure 6. (a) to (f) Slag Eye Opening Area after few seconds of Pouring of Liquid in the Bath

Figure 6. (g) & (h) Statistical representations of slag eye area after reaching the bath fluid flow in steady state

6. Slag Eye Study during Pouring with Argon Purging

Argon inert gas shrouding at the melt transfer inlet nozzle during melt flow to the bath of the tundish is a common technique in continuous casting metallurgy to remove unwanted inclusions and prevent re-oxidation from air to some extent such that product surface quality and internal soundness can be improved as well simultaneously submerged entry nozzle clogging can be minimized to remove unwanted interruption of plant operations [12]. Despite so many advantages the formation of exposed slag eye during gas shrouding is a critical problem [35]. 20% of the inlet water volume

fraction argon gas was injected at the inlet of the nozzle and VOF multiphase model applied to find the exposed slag eye area for all types of shroud and impact pad combinations as well as for newly innovative shroud also. Water (red color)-Oil (yellow) -Air (blue) -Argon (green) phases were depicted in the Figure 7 [(a)-(e)]. From Figure 7 (f) and (g) it is observed that for conventional shroud and trumpet shroud the slag eye area is enlarge due to high upward velocity and large diameter gas bubbles formations respectively. These two phenomena have high impact to sweep the upper phase slag more towards bath wall. Dissipative shroud and advance pouring box cases also produce enlarge slag eye but slightly less as compared to previously mentioned two shroud configurations. The newly developed vacuum shroud (VS)

also produce small slag eye area from argon shrouding effect which is very less than the earlier developed shrouding technology towards control of stability within the melt bath inside the tundish. So from the above details study related to slag eye area it can be easily identified

that vacuum shroud (VS) will be highly helpful to produce sound quality product by avoiding re-oxidation from exposed slag eye area and at the same time will help to remove inclusions build up inside the wall of the submerged entry nozzle immersed in the mold.

Figure 7. (a) to (e) Multiphase plot of Argon shrouding for different typed flow control device

(f)

(g)

Figure 7. (f) & (g) Graphical plot of density fluctuations at slag phase and slag eye area respectively

7. Effect of Increasing Pouring Velocity on Slag Eye for Vacuum Shroud

To judge the ultimate performance of this new device at extreme velocity conditions the performance of the newly developed flow control device was investigated by numerical simulation. The pouring velocity was increased from 2 meter/sec to 3 meter/sec, 4 meter/sec and 5 meter/sec and the effects of increasing velocity on possibility to formation of exposed slag eye. It is observed that up to increasing the velocity 4 meter/sec there is no possibility to formation of slag eye in the bath melt surface after application this innovative flow control device as shown in Figure 8 (a) and (b). But when the speed of the impinging fluid reaches 5 meter/sec there is sweep of the slag from the side wall of the bath as

exhibited in the Figure 8 (c). It is seen from the velocity contour plot Figure 8 (d), (e) and (f) that the intensity of upward velocity of fluid along the side wall gradually increases. For the above study the vacuum pressure within the side nozzle of the newly developed shroud maintain 750 torr. With extreme velocity condition like when initial pouring speed is enhanced to 5 meter/sec and simultaneously the vacuum negative pressure within the side nozzle of the newly developed fluid flow control device is reduced to 720 torr, then results shows remarkable improvement to reduce formation of exposed eye along the side wall of the bath as seen from the Figure 8 (g). So its negative vacuum pressure or suction nature at the side nozzle of the innovative shroud helps to retard the turbulence within the bath. Figure 9 (a) to (d) and (e) to (h) is the histogram distribution of the pressure and velocity plot within the

whole bath including nozzle portion also which clearly shows increasing negative pressure with increasing bath

velocity and increasing negative vacuum pressure decreasing the bath velocity distribution.

Figure 8. a.b.c.d.e

Figure 8. Multiphase and velocity contour plot of Vacuum Shroud (VS) during inflow rate of fluid at (a&d) 3 m/sec (b&e) 4 m/sec (c) 5 m/sec and (g) 5 m/sec with slightly high vacuum (720 torr pressure within the outer nozzle chamber) employed

Figure 9. a.b.c.d

Figure 9. Histogram distributions of static pressure (a) to (d) and velocity (e) to (h) within the Nozzle & Bath for Vacuum Shroud with increasing pouring velocity respectively

8. Effect of Slag Entrainment on Emulsification for Different Shroud Configurations

Emulsification of slag-metal and gas-slag-metal is a common observation in many metallurgical processes. It is basically dispersion of some immiscible fluids due to turbulence which has been discussed by physical modeling in literature [36]. The drawback of emulsifications in tundish metallurgy is that it contaminates the liquid metal which is harmful for the cast product mechanical properties. Some ladles contain large quantity carryover slag which has possibility to entrain into the tundish bath during ladle change over period as a result of vortexing phenomena inside ladle during drainage operation in turret of continuous casting machine sequence casting which cause emulsifications and high rate of inclusions generations within tundish liquid steel [37]. Efforts were made to suppress vortexing phenomena during ladle drainage operations by applications static magnetic fields which reduce the tangential velocity and 50% success was

reached by laboratory physical modeling in the study of some researchers [38]. So it can say that thick oxidize carryover slag entrainment still have a possibility to create emulsifications in tundish during ladle change over period. In the current study multiphase VOF (volume of fluid) model were employed to study the slag entrainment effect on emulsifications for different shroud and impact pad combinations flow control device and its comparison with newly conceptualize vacuum shroud (VS).

From the Figure 10 [(a) to (e)] it is observed that huge turbulence is pertaining at the melt (water-red color, oil-yellow color, air-blue color) during slag infiltrations period as well as a mixture of water-oil-air is formed on the surface of the fluid which has heavy tendency to entrapped within the water or melt. Figure 10 (f) is a graphical representations of density fluctuations along the slag phase during slag infiltrations which indicate that high emulsifications is possible for conventional shroud, dissipative shroud, trumpet shaped shroud and in the case of advanced pouring box. Relatively less emulsifications observed for vacuum shroud because it hinders the flow of total slag to reach inside the melt bath and partial entrained slag go to

the top surface of the outer nozzle of the shroud. So low density infiltrate slag floatation partially suppressed by this new flow control device. Figure 11 [(a)-(e)] is the multiphase plot of different phases after reaching stable operations from the emulsification period. For all shroud and impact pad combinations except vacuum shroud there is huge tendency to thinning and sweep of the slag layer

and ultimate result is towards oxidations of the liquid steel melt and generations of indigenous and exogenous inclusions. It is also understandable from the graphical density fluctuations plot as before at Figure 11 (f) that stability quickly reached for vacuum shroud which is not observed for other flow control shroud and turbostop combinations.

Figure 10. (a) to (e) Multiphase plot of initial period slag entrainment in the bath

(f)

Figure 10. (f) Graphical plot of emulsifications

Figure 11. a.b.c.d

(e)

(f)

Figure 11. (a)-(f) Conditions of the bath emulsifications after reaching steady state

9. Inclusion Floatation Characteristics for Different Shroud

Continuous casting technology is using dominantly over last three decades to almost 90% of the steel plants around the world due to its high yield and produce quality semi finished cast microstructure for steel structural and construction applications. For that reasons the steelmaker facing strict competitions to sale the product in market and at the same time high quality clean steel production is

paramount importance to the steelmakers which is possible by controlling fluid flow and inclusions floatation in tundish metallurgical vessel [39]. Tundish process performance is evaluated based on the inclusion floatation tendency of this metallurgical reactor and this can be enhanced by incorporating suitable furniture and flow control device which will desperately help to alter the flow pattern of fluid within this vessel as observed in the study of metallurgist [40]. Exogenous inclusions mainly generated due to re-oxidation in tundish, slag entrapment, lining erosions which have detrimental effect on cast

structure and to control this adverse effect on product state of art technology is required to develop for future sustainability [41]. Numerical simulation was applied by some researchers to evaluate the inclusion characteristics during ladle change over period and it was found that during this unsteady state inclusion percentage in the tundish as well as mold increases and also it is inferred that proper flow control device can enhance the inclusion removal rate in tundish during opening of new ladle in a sequence casting operation as clean steel is highly desirable for particularly high grade steel casting [42]. So it is highly desirable to judge the inclusion removal efficiency of different types shroud and impact pad combinations. As $50\mu\text{m}$ is the critical diameter of the inclusions as mentioned literature [30]. So it's floatation characteristics from stokes law were evaluated in current study. Discrete Phase Model (DPM) in FLUENT was used to evaluate the particle track and number of entrapped inclusions particles within the bath liquid. The velocity inlet, top surface of the bath and the top surface of the outer nozzle of vacuum shroud were used escape boundary conditions for rigid inclusions particles and remaining boundary wall treated as reflected the spherical particles. The details simulation parameters can be

obtained from Table 1 and Table 2. Figure 12 [(a)-(e)] is the particle velocity magnitude plot for different shroud and impact pad combinations. Figure 12 (f) indicates that trumpet shroud is less efficient to float maximum inclusions due to its bell shaped nature at bottom which entrap inclusions much in the bell region. Conventional shroud, dissipative shroud and advanced pouring box system shows similar characteristics in terms of inclusions removal from bath. Exceptional characteristics observed for newly concept shroud which is highly efficient to remove detrimental inclusions particles. Figure 13 [(a) - (e)] depict particle trajectory for all shroud designs and it is observed that maximum inclusions have a chance to flow along the nozzle wall which is also exhibited in the Figure 12 [(a) – (e)]. Less no of inclusions tendency is to go towards bath wall after impinging the fluid on the bath. It is observed that those particles reach to the side wall of the bath; they have a less probability to float quickly to the slag phase as they will experience less upward velocity and have to travel more paths to float to the upper phase. In case of vacuum shroud the trajectory is different than other shroud configurations as vacuum induce inclusions floatation's at the outer nozzle of the shroud and partially some particles will escape through the bath slag phase.

Figure 12. a.b.c.d

(e)

(f)

Figure 12. (a) to (e) Velocity magnitude plot of inclusions particles for different shroud configurations (f) Statistical representations no. of inclusions entrapped within the bath

When the molten steel is transferred from ladle to tundish there is a chance to oxidize the liquid steel by air aspirations from the wall as a result of leaking due to sudden drop of pressure within the shroud from its changes of diameter i.e. decrease or enlargement which can be avoided by argon injection from the side wall of the submerged nozzle [43]. Gas shrouding not only decreases oxidation, it helps to remove unwanted inclusions, dissolve gas removal, enhance plug flow and avoid thermal stratifications in the vessel [44]. Figure 14 [(a) to (e)] depict effect of argon shrouding on the inclusion floatation characteristics. As during transfer operations due to re-oxidation large size inclusions are formed so in the current case 50 μm diameter inclusions

are taken into consideration for study [45]. It is observed that the same trend as before seen from the Figure 14 (f) plot that trumpet shaped shroud is less efficient and vacuum shroud is highly promising to reduce inclusions entrapment within the tundish. 10 mm diameter argon bubbles were taken for current research which is seen as red color in the Figure 14 [(a) to (e)] and blue color particles represents the inclusions for different shroud designs. Figure 15 [(a) to (e)] indicates particle trajectory path which shows the same nature of particle flow as explained earlier for normal inclusions floatation condition for different shroud configurations. From the simulation study it is also noticed that after argon purging at moderate rate for vacuum shroud the probability to float

the inclusions within the side vacuum chamber is increased. Sometimes high rate of gas injection are inserted from the injection hole to the downward driven flow. The effect of high rate argon gas injection on the inclusions flow ability characteristics were studied in the present research which has been exhibited in the Figure 16 [(a) to (e)]. It is understand from the particle distribution plots for different types of shroud that the argon particle flow is mainly concentrating near the outside of the nozzle shroud instead of flowing whole the bath fluid as experienced in the earlier discussion where moderate argon flow were employed. Figure 16 (f) plots also support the inefficiency characteristics of the trumpet shaped shroud and high efficiency of the vacuum shroud (VS) in the context of inclusions floatation. It is observed from the Figure 14 (f) and Figure 16 (f) comparisons that the number of argon particles within the melt decreases for high purging shroud and the number of entrapped inclusions particles are increasing within the melt. This is happening as with increasing argon purging the volume fraction of gas within the nozzle increases which make a low density fluid and as a result the diameter of the argon bubbles are increased which has high stokes terminal velocity to escape as mentioned in literature [46]. Due to formations of large size argon bubbles it also get hinder to flow towards bath wall and as a result inclusions floatability suppressed and argon

particles unable to help the inclusions particles to flow rapidly on the top surface of the melt. Figure 17 [(a) to (e)] indicates that with increasing argon purging the inclusions particles floatability limited to a narrow region near the shroud wall for all shroud configurations and inclusions which will flow through the vacuum shroud will be entrapped within the nozzle itself. Hence from the above study it can be suggested that the new shroud not only help to reduce turbulence during metal transfer from ladle to tundish, it will also helps to reduce inclusions content within the tundish bath. Heavy argon gas injection change the flow movement of fluid towards more upward which intense the turbulence level within the liquid steel and narrow the back flow region [47]. This type of fluid flow pattern decreases the probability of inclusions floatation during melt flow from ladle to tundish through submerged pouring tube as readily understandable from the current investigation. During turbulence small size inclusions floatability enhanced and simultaneously due to collisions large size inclusions chances of attach with upper slag phase decreased [48]. That is one of the causes of entrapment of more inclusions with increasing argon purging rate at the side wall of the shroud pouring nozzle normally used. The new device has no such problem due to its superior control over turbulence in pouring fluid from ladle to tundish.

Figure 13. a.b.c.d

Figure 13. (a)-(e) Trajectory Plots of Inclusions particles

Figure 14. a.b.c.d

(e)

(f)

Figure 14. Discrete phase entrapped particles distribution plots (a)-(f) for inclusions (blue color) and inert argon particles (red color) during gas shrouding

Figure 15. a.b.

Figure 15. (a) - (e) Trajectory Plot of particles during argon shrouding condition

Figure 16. a.b.

Figure 16. (a) – (f) Distributions of argon and entrapped inclusions during high rate of gas shrouding condition

Figure 17. (a) – (e) Chances to flow the particles during modified flow conditions due to high rate of gas impinging from the side wall of the shroud

Figure 18. Statistical plot of oxygen pick up rate from slag eye at different period of operations for all shroud configurations

10. Rate of Oxygen Pick up Predicted from Regression Model for Different Shroud Configurations and It's Compared with Vacuum Shroud

The steel cleanliness is measure by amount of non metallic inclusions present in the liquid melts with morphology etc. but there is no single method to quantify steel cleanliness and total oxygen, nitrogen pick up in the melt is widely acceptable method to measure the steel inherent quality [49]. So it is highly desirable to quantify the effect of slag eye on the rate of oxygen pick up for different shroud and impact pad combinations with its comparison to newly conceptualized shroud which has been plotted in the Figure 18. The rates of oxygen pick up with open eye were calculated based on the following empirical correlation equation (12) developed by some researchers [50].

$$R_{O_2} = 47.265d^2 + 20.798d - 2.495. \quad (12)$$

It is observed from the above mentioned plot that conventional and dissipative shroud with turbostop have greater possibility to pick up oxygen and nitrogen and on the other hand instead of oxygen pick up vacuum shroud (VS) will help to reduce unwanted dissolved gases within the liquid steel. At argon gas shrouding situation all types of pouring nozzle will exhibit high oxygen pick up rate except vacuum shroud which will help to pick up oxygen at reduce rate. One of the literatures embodied a practical image of slag eye where four zones are observed like bare metal, thin slag, fluid slag and crusty slag [51]. The thin and fluidic slag layer near the open eye region captured very little amount inclusions particles which is also proof by physical model investigation of the some researchers [52]. Although the total oxygen generally measure near

the stopper rods of the tundish but it is observed by some metallurgists that inclusions mainly concentrated at the region if slag eye of the tundish during steady state and unsteady state conditions [53]. So it is desperately require to control turbulence, slag eye generations, slag entrainment, inclusions float out during flow of liquid from ladle to tundish transfer operations to improve the yield and quality of steel on a sustained basis.

11. Conclusions

From the above numerical study the following conclusions can be drawn:-

- Conventional shroud, trumped shaped shroud and dissipative shroud with impact pad as well as to some extent after use of advanced pouring box instead of turbostop affect poorly on tundish process performance by forming large size slag eye during steady and unsteady operation which can be avoided by using the newly developed shroud. So it can say that this innovative shroud will able to wipe out the use of impact pad forever.
- Emulsifications and slag entrainment during ladle change over operations have detrimental effect on product quality which also can be reduced by this new flow control device other than the different shroud and impact pad readily available in the market.
- By producing plug flow of incoming fluid in tundish from ladle and argon shrouding at the pouring nozzle it is attempted to float inclusions on the tundish flux which is not so much beneficial observed from current investigation where the vacuum shroud have much capability to reduce inclusions entrapment within the tundish melt.
- It also can be suggested that the newly conceptualized shroud will help to extract unwanted

dissolved gases from the flowing fluid at tundish inlet.

- It will also reduce the blow-back action of high temperature fluid during ladle changing period and will be able to improve the operator safety.
- At the end it can infer that this novel green control device will help to reduce the refractory erosion within the tundish.

12. Future Study

As a future scope of the current study water modeling and some numerical simulation in a full scale tundish is required to further judge the prospect of the current innovation and repeated plant trial in integrated steel plant is prerequisite to give it a final shape and make it patentable. Non isothermal study is also required for knowing the effect of this green flow control device (FCD) on superheat, residence time distribution (RTD) and thermal stratification at tundish vessel.

Nomenclature & Abbreviations

k: Turbulence Kinetic Energy per unit mass, m^2/s^2
 Re: Reynolds number
 ϵ : Energy dissipation rate, m^2/s^3
 d_p : Diameters of Particles, m
 ρ_p : Density of the particles, kg/m^3
 u_p : Velocity of Particles, m/s
 $C_1, C_2, C_\mu, \sigma_k$ and σ_ϵ : Constants
 ρ : Fluid Density, kg/m^3

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