Role of Tundish Argon Diffuser in Steelmaking Tundish to Improve Inclusion Flotation with CFD and Water Modelling Studies

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***Abstract* - Investigation on inclusion removal by bubble flotation method in a two-strand tundish was carried out using computational fluid dynamics and through water model studies. Recently, a new technique of gas curtain made of small bubbles of argon called Tundish Argon Diffuser has been used to remove the finer inclusions from steel in order to produce clean steel. Aim of this work was to find out the effect Tundish Argon Diffuser on the efficiency of inclusions removal and on optimization of its location for plant conditions. Both Physical and Numerical simulations were carried out in a 1:4 scaled down model for tundish of 50T capacity of Bokaro Steel Plant, India. Numerical simulations were carried out using ANSYS FLUENT CFD software. For physical modeling study, water model was used for fluid flow, residence time distribution and inclusion flotation studies. Results from both studies suggested that the use of tundish argon diffuser enhances the surface directed flow which in turn improves inclusion flotation and also reduces metal loss due to better mixing and lesser dead zone. Fluid flow analysis showed lesser turbulence on the free surface which lead to lesser de-oxidation of liquid steel after using Tundish Argon Diffuser. Location of Tundish Argon Diffuser needs to be optimized in order to get maximum benefit. For Bokaro Steel Plant conditions, placement of Tundish Argon Diffuser at 2400mm at both sides from the center gives the best result compared to all other locations.**

Keywords: Computational Fluid Dynamics, Water modeling, Tundish, RTD analysis, Inclusion flotation

1. INTRODUCTION

The steel tundish in continuous casting not only acts as a storage vessel, but also acts as an additional metallurgical unit where other operations such as control of melt temperature, composition etc. and melt flow control are performed in order to promote non metallic inclusion separation. Increasing demands from customer for the production of high-quality steels, led to the development of new technologies in tundish for removal of inclusions from liquid steel. Non-metallic inclusions, such as sulphide, silicate and aluminates particles, are formed during the steelmaking process. If these inclusions are large enough and are entrapped within the steel melt they often lead to undesirable defects in steel products. For steel to be termed 'clean', it must have a low level of residuals. The dynamics of melt flow is a key factor in controlling the inclusions flotation. Non-metallic inclusions of sizes smaller than 15 µm are difficult to remove, as they do not float easily. They are carried by the flow of steel melt into the mould which adversely affects the steel cleanliness. It is suggested that a gas curtain made of small bubbles of argon called Tundish Argon Diffuser (TAD) as shown in Fig.1 may be used to capture and remove these inclusions in the tundish, thus avoiding their transportation into the mould.

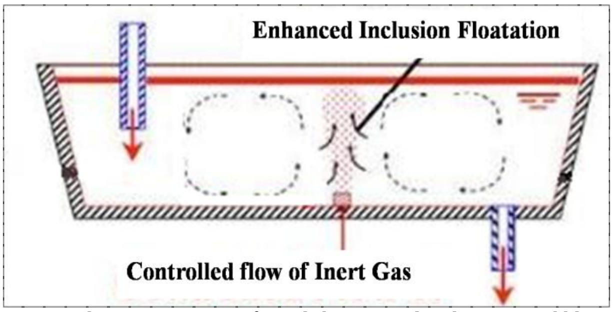

Fig. 1: Schematic Diagram of Tundish Equipped with Argon Bubbling

Steel flow or inclusions separation studies at the industrial scale are difficult because of high temperature and a lack of optical accessibility. Therefore, investigations are performed with computational fluid dynamic (CFD) and water modelling studies. Investigations with water models are already well known and are widely applied [1-4]. Flow visualisation measurements of the residence time distributions, transient zone, influence of different flow control devices on steel flow, and particle separation are a few examples of this technique. A large number of tundish flow and particle separation studies have been performed with using numerical modelling as well [5-7]. Physical models are often used in combination with numerical model and the investigated phenomenon is often validated using experimental results of water model.

A. Ramos-Banderas, R. D. Morales, L. Garcia-Demedices and M. Diaz-Cruz[8] in their study, investigated removal of non-metallic inclusion from liquid steel in tundish through two-phase flow modeling by using Particle Image Velocimetry (PIV) techniques and through numerical simulation. They found that removal efficiency of gas bubbling in tundish becomes independent of particle size and of flow control device (FCD) arrangements. An increase in mass flow rate decreases the particle mean residence time in tundish and therefore reduces the removal efficiency. Zhang, L. and Taniguchi, S [9] have reviewed the fundamentals of inclusion removal from liquid steel by attachment of the inclusions to rising bubbles. Zhang and Taniguchi's study provides an overview of the mechanisms of bubble/inclusion interaction and also provided a model for inclusion removal by bubbling in batch processes like ladle stirring. J. de J. Barreto S., M. A Barron MEZA, and R D Morales[10] have proposed that bubbling in a tundish could remove small inclusions. A cold model study on inclusion removal has demonstrated that fine particles can be readily sensitive to fluid depth, casting rate, and gas flow rate & bubbler position. A numerical model has been developed to predict the effect to the above parameters on inclusion removal.

The present study investigates the effect of Tundish Argon Diffuser on the efficiency of inclusion removal inside the tundish. Both CFD and water modelling studies have been carried out in a 1:4 scaled down model for tundish of 50T capacity of Bokaro Steel Plant (BSL). Numerical simulations were carried out using ANSYS FLUENT CFD software. For water modelling study, water model was used to observe/measure the fluid flow, residence time distribution and inclusion flotation.

2. CFD MODELING

Numerical simulations were carried out using ANSYS FLUENT CFD [1] software. For convenience and for better understanding, numerical model studies have been summarized under following three main headings.

- Fluid Flow
- Residence Time Distributions, and
- Inclusion Transport and Separation.

Fig. 2 shows the dimensions and meshed geometry of tundish which was used for simulation studies. Fluid flow has been simulated using k-ε turbulent model, species transport technique has been used for residence time distribution (RTD) analysis and discrete phase model (DPM) technique has been utilised to investigate inclusion flotation. Material properties of the liquid steel and modelling parameters used in the numerical simulation are given in the Table-1.

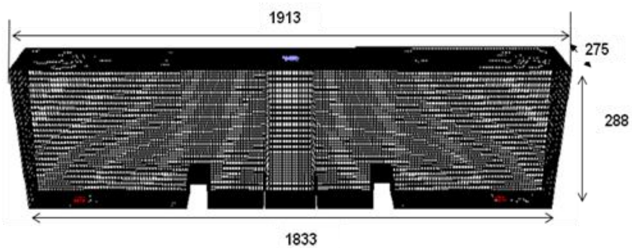

Fig. 2: Dimensions and meshed geometry of Tundish (in mm)

Table 1: Physical Properties of Liquid Steel and Modeling Parameter

Property	Value	Unit
Density	7000	Kg/m^3
Molecular Viscosity	0.00555	$Kgm^{-1}s^{-1}$
Inclusion density	3500	Kg/m^3
Parameters		
Mass flow rate in actual tundish	36.5	Kg/s
Mass flow rate in model tundish	1.2375	Kg/s

2.1 Governing Equations

a) Fluid Flow

The numerical model designed for the simulation of liquid steel flow in the tundish will include differential equations of continuity of flow and conservation of momentum. The flow profile of the tundish in the present study is calculated using standard turbulent equations of the k-ε model expressed in their three-dimensional version with standard wall functions[2].

Continuity equation can be expressed as eq.(1)

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho U_i) = 0 \quad (1)$$

In any flow (viz. Oxygen furnace, ladle, tundish etc.) the balances among the various forces acting on a fluid element can be described by the Navier-Stokes equation. For single phase, 3D flows in mettaturgical tundishes operating under steady state, isothermal, turbulent flow condition, the momentum balance on an elementary volume of liquid steel can be expressed as given below in eq(2), with two equations for turbulent kinetic energy and turbulent dissipation rate in eq(3) & eq(4) respectively.

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_i} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \quad (2)$$

$$\rho \frac{\partial k}{\partial t} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k - \rho\varepsilon \quad (3)$$

$$\rho \frac{\partial \varepsilon}{\partial t} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (4)$$

The effective co-efficient of viscosity is expressed by the formula below

$$\mu e_{ff} = \mu + \mu_t \quad (5)$$

Where the dynamic coefficient of turbulent viscosity is defined by the formula

$$\mu_t = C\mu\rho\frac{k^2}{\varepsilon} \quad (6)$$

Where the production term of turbulent energy is equal to

$$G = \mu_t \frac{\partial u_j}{\partial x_i}\left[\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \quad (7)$$

Constants used in the k-e model[1] (Launder and Spalding, 1974) are given in the table-2.

Table-2: Constants used in the K-ε Model

$C_{1\varepsilon}$	$C_{2\varepsilon}$	C_{μ}	σ_k	σ_ε
1.44	1.92	0.09	1.0	1.3

(b) Residence Time Distribution

Residence Time Distribution (RTD) is statistical representation of the time spent by an arbitrary volume of the fluid in the tundish. This has been simulated by solving a transient three dimensional convection along with diffusion equation, as given below.

$$\frac{\partial(\rho m_i)}{\partial t}+\frac{\partial(\rho u m_i)}{\partial x}+\frac{\partial(\rho u m_i)}{\partial y}+\frac{\partial(\rho u m_i)}{\partial z}=\frac{\partial}{\partial x}\left(\Gamma_{eff}\frac{\partial m_i}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{eff}\frac{\partial m_i}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_{eff}\frac{\partial m_i}{\partial z}\right) \quad (8)$$

$$\Gamma e_{ff}=\Gamma_m+\Gamma_t \quad (9)$$

(c) Inclusion Transport and Separation

The movement of inclusion particles in the liquid melt was tracked using the Discrete Phase Model. The Discrete Phase Model in essence is a combined Lagrangian-Eulerian calculation procedure. The equation for the inclusion transport can be written as follows.

$$\frac{dU_i^p}{dt}=\underbrace{-\frac{3}{4}\frac{\mu_l}{\rho_l d_b^2}C_d\,\mathrm{Re}_b\left(U_i^p-U_i\right)}_{Drag\ force}+\underbrace{\frac{\rho_l}{\rho_p}\frac{dU_i}{dt}}_{Pressure\ force}\underbrace{-\frac{1}{2}\frac{\rho_l}{\rho_g}\left(\frac{dU_i^p}{dt}-\frac{dU_i}{dt}\right)}_{Virtual\ mass\ force}+\underbrace{\left(1-\frac{\rho_l}{\rho_p}\right)g_i}_{Bouyancy\ force} \quad (10)$$

2.2 Initial and Boundary Conditions

The boundary conditions for momentum transfer are those of no slip at the solid surfaces and zero normal velocity gradients on the free surface of the liquid. In a similar way, both k and ε are assigned through turbulent intensity (5%) and through hydraulic diameter correlations. For inclusion flotation simulation, particles are allowed to reflect from all the walls of the tundish and are allowed to escape from the outlet. For RTD analysis, all walls and free surface are considered to have zero diffusive flux.

2.3 Numerical Solution of the Governing Equations

The governing equations of flow, turbulence and the associated transport processes have been solved numerically by adapting the finite difference calculation procedure. The coupled three dimensional, non-linear, partial differential equations were solved numerically with second order upwind discretization scheme by using SIMPLE algorithm. Convergence criteria of 1e-06 were fixed for all equations other than those for RTD, in which case the convergence criteria were below 1e-12. Time step of 1s with approximately 100 iterations in each time step for a total duration of 4000 s was utilized to generate RTD curves.

3. WATER MODELING

In the present work, the ratio of geometrical similarity of model tundish to the prototype was chosen to be 1:4. Dynamic similarity require simultaneous equality of both turbulent Reynolds and Froude numbers, though it was very difficult to keep the condition satisfied in reduced scale modeling studies. The computational work of Sahai and Burval[11] and the experimental work of Singh and Koria[12] showed that the magnitude of Reynolds number under turbulent flow range in different tundishes were very similar. Therefore, Froude number between the model tundish and the prototype was maintained as equivalent in this work. Table-3 shows that the kinematic viscosities of water at 20 ^{O}C and steel at 1600 ^{O}C are similar indicating comparable levels of Froude number in the model as well as prototype. Thus water at room temperature can easily replace liquid steel for physical experimentations.

Table 3: Comparison of Physical Properties of Water at 20^{o}c and Steel at 1600^{o}c

Property	Water at 20^{O}C	Steel at 1600^{O}C	Unit
Dynamic Viscosity	0.001	0.0064	$Kg.m^{-1}.s^{-1}$
Density	1000	7014	$Kg.m^{-3}$
Kinematic Viscosity	1.10^{-6}	$0.913.10^{-6}$	$m^2.s^{-1}$
Surface Tension	0.073	1.6	$N.m^{-1}$

4. RESULTS AND DISCUSSION

4.1 Model Validation

RTD curve analysis is the most common technique to estimate the particle separation and to analyse flow conditions. The experimental results were obtained by pulse tracer addition technique in a water model. Numerical results were calculated using CFD simulation. For both the conditions, simulations were carried out for different tundish configurations according to the location of DAM and TAD. These are shown in the Table-4. Figure 3 shows the comparison of experimental and predicted results with the similar conditions. It is observed that there is good agreement between CFD and water model studies though there is a small shift in the peak of the RTD curves. This is possibly due to the difference in diffusivity values.

Table 4: Different Tundish Design Configurations

	Arrangement of DAM		Arrangement of TAD	
	Location, mm	Dimension, mm	Location, mm	Dimension, mm
	from center	width X height	from center	width X height
Case-1	1800	300 X 200	NO TAD	NO TAD
Case-2	1800	300 X 200	2100	200 X 120
Case-3	1800	300 X 200	2400	200 X 120
Case-4	NO DAM	NO DAM	1800	300 X 200
Case-5	NO DAM	NO DAM	2100	300 X 200
Case-6	NO DAM	NO DAM	2400	300 X 200

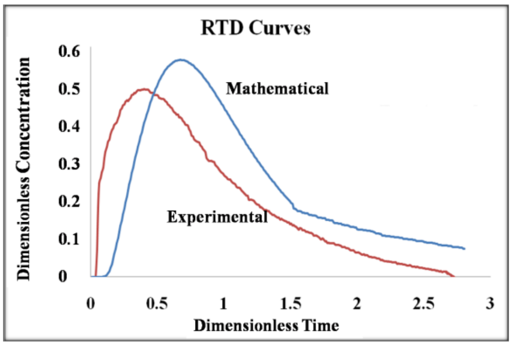

Fig.3: Comparison of experimental and predicted results

4.2 RTD Analysis

Table-5 shows the RTD analysis results of numerical simulation for different arrangements of DAM and TAD in the tundish. From the above analysis it is observed that case-1, case-2 and case-4 show similar results of less minimum residence time (MRT) and higher dead volume. These in turn are favourable for homogenization though they are not satisfactory conditions for inclusion flotation. Case-1 is the existing condition without TAD. Case- 2 and case-3 are combinations with TAD. Even these results showed less MRT because of the location of TAD. In rest of the cases, when TAD was used as one of the flow modifiers (case-3, case-5, and case-6), it resulted in increased MRT, increased plug volume and reduced dead volume. This in turn gave rise to improved inclusion flotation and to reduced skull formation in the dead area. Use of dam only as flow modifier resulted in less value of MRT and less plug volume. They also lead to higher dead and mixed volume. Hence, it can be concluded that TAD location plays a vital role in the enhancement of tundish performance. From this table it is also observed that the ratio of plug volume to dead volume and the ratio of plug volume to mixed volume are high for case-3, 5 and 6. These lead to better mixing and homogenization of metal inside the tundish.

Table 5: RTD Analysis from CFD Modeling

	MRT, s	% V_{dp}	%s V_d	% V_m	V_{dp}/V_d	V_{dp}/V_m
Case-1	1800	26	24	50	1.08	0.52
Case-2	1808	28	23	49	1.22	0.57
Case-3	1940	38	15	47	2.53	0.81
Case-4	1816	22	25	53	0.88	0.42
Case-5	1928	37	16	47	2.31	0.79
Case-6	1968	39	15	46	2.60	0.85

Table-6 shows the RTD analysis results from experiments on water modelling. It is observed that case-6 gives higher values of MRT, less dead volume and more mixing volume as compared to all other cases of tundish configuration. High value of MRT leads to more inclusion flotation to the slag layer. It can be said that TAD helps to produce cleaner steel.

Table 6: RTD Analysis from Water Modeling

	% V_{dp}	%s V_d	% V_m	MRT, s	V_{dp}/V_d	V_{dp}/V_m
Case-1	12	26	63	1592	0.46	0.19
Case-2	10	24	60	1620	0.42	0.17
Case-3	12	18	70	1756	0.67	0.17
Case-5	12	23	65	1640	0.52	0.18
Case-6	10	16	74	1804	0.63	0.14

4.3 Inclusion Flotation Analysis:

Fig.4 and Fig.5 shows the inclusion flotation inside the tundish with and without tundish argon diffuser from CFD and water modeling respectively. From Fig.4 (a) and 5 (a), it can be seen that inclusions coming from the inlet moves towards outlet. In the presence of DAM some amount of liquid moves towards the surface. Also maximum amount of the liquid with inclusion move towards the outlet. Therefore, it can be said that case-1 is not favorable for inclusion separation. However, in case of case-6 (Fig.4 (b) and 5(b)), it can be observed that due to the presence of gas curtain, most of the liquid with inclusions initially tries to move towards the top surface and then comes down to the outlet. At the surface of the tundish, liquid slag captures the inclusions.

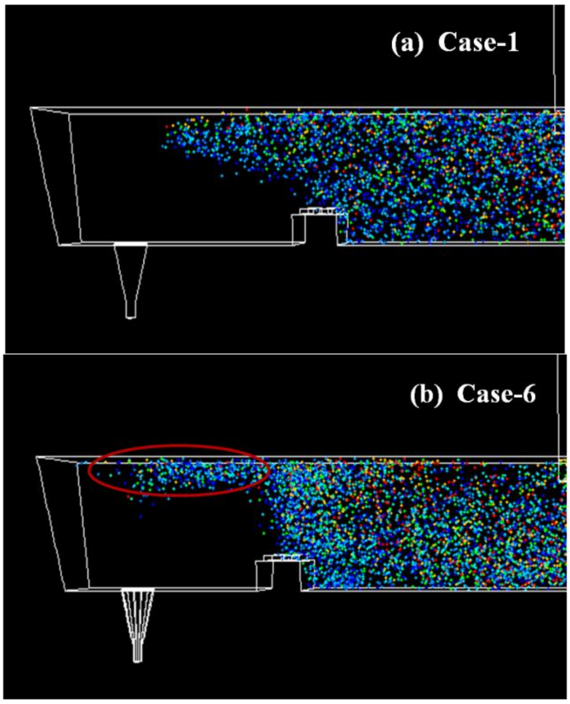

Fig.4: Inclusion flotation inside the tundish (a) without TAD and (b) with TAD from CFD modelling

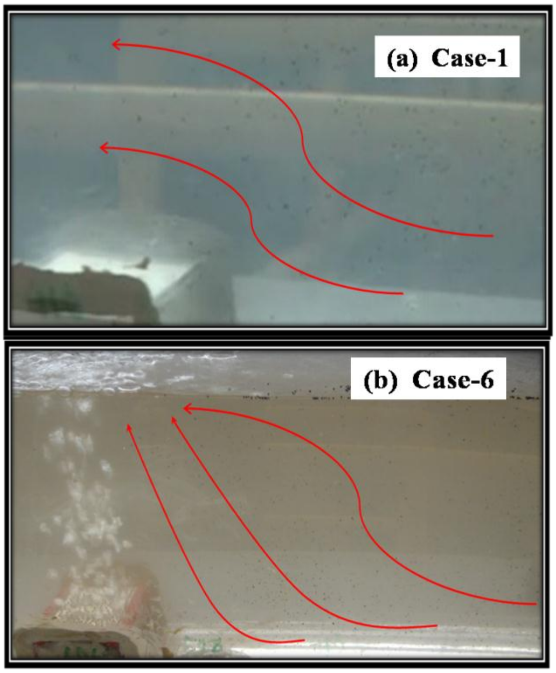

Fig.5: Inclusion flotation inside the tundish (a) without TAD and (b) with TAD from water modeling

4.4 Fluid Flow Analysis

Fig.6(a) and (b) show the velocity profiles from CFD modeling for the existing tundish and for proposed case-6 tundish configuration respectively. It is observed that in case of the existing tundish, there is highly turbulent flow at the inlet. This flow is comes back to the inlet due to the presence of DAM. Though DAM helps in surface directed flow, it also increases the dead zones. Fig.6 shows flow profile inside the tundish using color die injection (a) without TAD and (b) with TAD in the water modeling. It is observed that the flow is more uniform throughout the tundish with more surface directed flow owing to the presence of TAD. Argon bubbles coming from the TAD help in moving the liquid towards the slag surface where inclusions get captured at the slag layer. Also, case-6 is shows higher mixing zone and less dead zone compared to the existing tundish configuration. This resulted in reduction of metal loss due to higher mixing and lesser dead zone. The fluid flow analysis (Fig.6&7) suggests that use of tundish argon diffuser enhances the surface directed flow which in turn improves inclusion removal and also shows lesser turbulence on the free surface which lead to lesser de-oxidation of liquid steel compared to existing tundish.

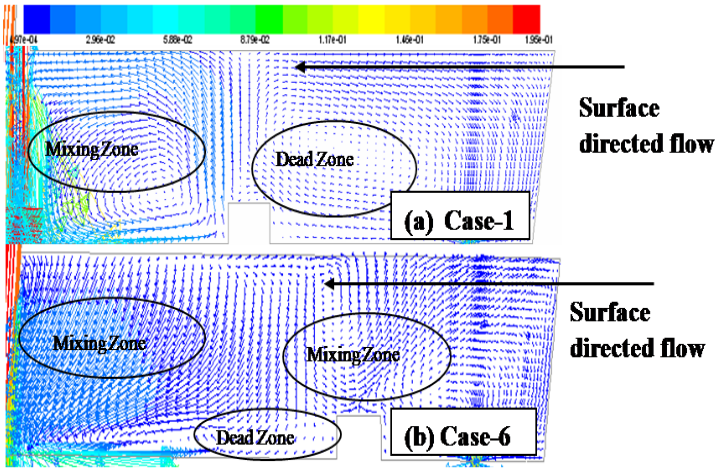

Fig.6: Velocity vectors colored by velocity magnitude of the flow inside half of the tundish from the center line (a) without TAD and (b) with TAD using CFD modeling

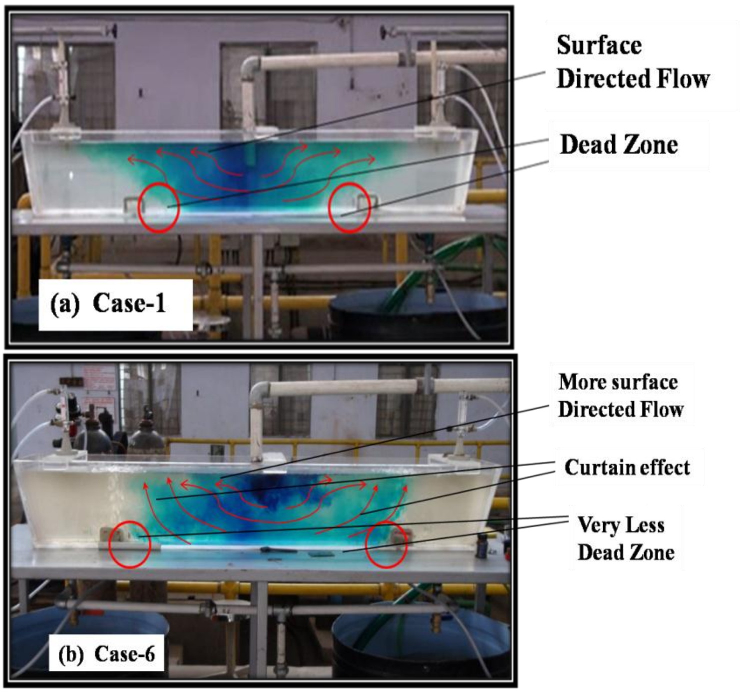

Fig.7: Flow profile inside the tundish using color die injection (a) without TAD and (b) with TAD in the water modeling

5. CONCLUSIONS

In this study a reduced-scale water model of a two-strand tundish was developed for the slab caster tundish of Bokaro Steel Plant. The model was then used to perform residence time distribution (RTD) experiments to determine the flow behavior of six different tundish design configurations. ANSYS FLUENT CFD model was also used to simulate the behavior of fluid flow, RTD and inclusion floatation inside the tundish. Combined CFD and water model studies were carried out in a model of slab caster tundish of Bokaro Steel Plant to investigate the efficiency of Tundish Argon Diffuser to improve the inclusion floatation in the tundish. The mathematical model was successfully validated against the water model results and also suggested good agreement between them. The following conclusions can be drawn from the above study.

- Tundish argon diffuser enhances the surface directed flow which in turn improves inclusion removal compared to the existing tundish.
- Use of TAD resulted in reduction metal loss due to higher mixing and lesser dead zone.
- Fluid flow analysis showed lesser turbulence on the free surface which lead to lesser de-oxidation of liquid steel after using TAD.
- Location of TAD needs to be optimized in order to get maximum benefit of TAD for improved inclusion flotation during production of clean steel.
- The numerical model was successfully validated against the water model results. Good agreement was observed between them.
- For BSL conditions, TAD at 2400mm at both sides from the centre gives best results compared to all other locations.

NOMENCLATURES

C_d	:	Coefficient of discharge
g	:	Acceleration due to gravity, m/s^2
m_i	:	Mass fraction or concentration of an injected tracer, *i*
G_k	:	Turbulent kinetic energy
R_e	:	Reynolds number
U	:	Mean liquid steel velocity component in i direction (m/s)
U^p	:	Velocity of inclusion particle, m/s
V_{dp}	:	Dispersed plug volume fraction
V_d	:	Dead volume fraction
V_m	:	Mixed volume fraction

Greek symbols

Γ_{eff}	:	Effective exchange coefficient for transport of inclusion
τ	:	Theoretical Average Residence Time, s
ρ_l	:	Density of the liquid, kg/m^3
ρ_{dp}	:	Density of the inclusion particle, kg/m^3
ρ_g	:	Density of the gas, kg/m^3
κ	:	Turbulent kinetic energy, m^2/s^2
ε	:	Turbulent dissipation rate, m^2/s^3
μ_{eff}	:	Effective viscosity, N/ms
μ_l	:	Liquid viscosity, N/ms
σ	:	Surface Tension, N/m^2
ζ	:	Normally distributed random number

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