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FLUID FLOW CHARACTERISTICS AND RTD ANALYSIS OF A SINGLE STRAND TUNDISH

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ABSTRACT

The mathematical modelling of the fluid flow and heat transfer behaviour of the steel melt in the tundish is carried out for a single strand tundish. The flow dynamics and heat transfer in the tundish is analysed by presenting the velocity field, Residence time distribution (RTD) curves and the temperature profiles by changing the geometrical parameters such as the width, the bath height, their simultaneous change and the nozzle distance of the tundish. The RTD curve is used to find the different volumes such as plug volume, dead volume and mixed volume inside the tundish. The ratio of mixed to dead volume, which indicate the mixing capability of a tundish, is estimated. Heat transfer analysis is carried out under steady state conditions for the constant heat fluxes from walls and from free surface of the tundish, for the above mentioned parametric changes so as to find out tundish steel melt cooling rates to determine the lowest temperature zones (maximum cooling), which are the indications of the dead volume regions during the steel flow. It is observed that the increase in the dead volume fraction proves detrimental for mixing. The value of the dead volume is found to be more sensitive than the other two volumes to find mixing capability and hence important to reduce this stagnant portion as far as possible. It is concluded that the validation presented for the two cases is quite satisfactorily close to the experimental observations reported in the literature.

NOMENCLATURE

C	*Concentration of tracer*
Fr	*Froude number*
Gr	*Grashoff number*
Ji	*Diffusion flux of species*
Re	*Reynolds number*
Ret	*Turbulent Reynolds number*
RTD	*Residence Temperature Time*
T	*Temperature*
U	*Velocity*
V	*Volume of tundish*
Yi	*Mass fraction of species*
g	*gravitational acceleration*
h	*enthalpy*
k	*Turbulent kinetic energy*
k_{eff}	*Effective conductivity*
x,y,z	*Cartesian coordinates*
P	*Pressure*
t	*Time*
ε	*Dissipation rate of turbulent kinetic energy*
μ	*Liquid viscosity*
ν	*Kinematic viscosity*
ρ	*Liquid density*
δij	*Kronecker delta function*
σ_c	*Turbulent Schmidt number*
σ_k	*Turbulent Prandtl number for k*

INTRODUCTION

The growing demands on quality in steel products during the past couple of decades have made continuous casting of steel a widely used process and an important step in the manufacture of steel. Fig. 1 depicts major components of the continuous casting process. The tundish an integral part of this process is an intermediate vessel located between the ladle and the mold so as to maintain the continuity of the casting process by keeping constant bath height over the mold. It is traditionally regarded as a reservoir and manifold (Kovac et. al.(2003)), made of refractory materials. This has the primary functions as to hold sufficient liquid steel to provide constant head over the mold and permit ladle exchange to occur without interruption of sequence casting, thus forms the casting process continuous. Being a manifold, it facilitates the control of steel flow into the mold because it has a constant and lower hydrostatic head than the ladle. Tundish is filled with steel to its normal steady-state level before pouring into the mold starts, which is important during start up of the caster. Another important function is to float out the inclusions for cleanliness of the cast product.

Practically there are various types of tundishes being used but a unique optimum tundish design does not exist. The geometrical parameters of the tundish are primarily dictated to control fluid flow in the tundish. Residence time is a very important characteristic of any tundish flow. With knowledge of the residence time, tundish provides an excellent opportunity to perform the metallurgical treatments like inclusion separation, flotation, alloy trimming of steel etc. The efficiency and optimization of these metallurgical treatments require a close control of the molten steel flow characteristics in the tundish. Therefore a detailed knowledge of behaviour of steel melt in the tundish is necessary so that the conventional tundish can be made amenable to perform the metallurgical treatment during the process of continuous casting. Residence Time is defined as the time, a single fluid element spends in the vessel.

τ = tundish volume/ volumetric flow rate

Fluid flow in the tundish can be considered as consisting of well mixed, plug flow and dead volumes. The flow motion in these three regions is different. In the mixed

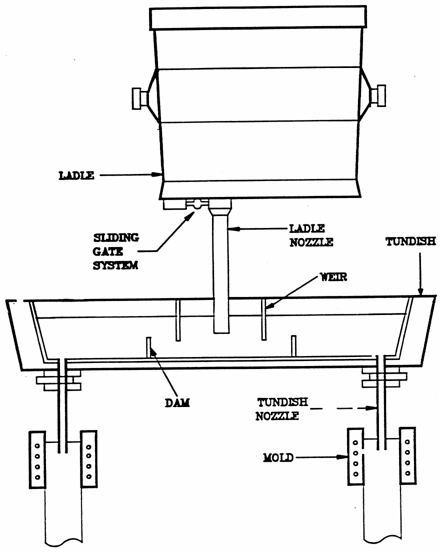

Figure 1: Schematic of a continuous casting process

region, fluid is dominated by inertia or viscosity. In the plug flow region, the dominant force is viscosity. In dead region the flow is stagnant.

In the perfectly mixed flow, the Fluid elements disperse instantaneously and uniformly throughout the system. At any time the concentration at the exit must be equal to that of inside the vessel. In plug flow, all the fluid elements travel through the vessel at nearly same speed and preserve their identity (i.e. they do not mix) during their passage. The Dead volume is the region where some fluid elements spend much longer than the mean residence time. Normally it is the region where fluid spends more than twice the mean residence time and the average fluid velocity is much smaller compared to the well mixed region. The high temperature together with the visual opacity of the liquid steel and relatively large sizes of the industrial tundishes makes the processing units cumbersome for direct experimental measurements and virtually impossible for the visual observations. Therefore reduced scale water models (transparent) using water as the simulating fluid has often been used to investigate transport processes within the tundish as it has been found that water at 20^{o}C and molten at 1600^{o}C have practically equivalent kinematic viscosities making reduced scale water model an excellent tool for investigations. Significant contributions in the past, includes numerical simulations of continuous slab caster by Ramirez et.al.(2000). Kovac et al.(2003), with their experimental methods worked on the precise employment of a turbulence inhibitors i.e. turbo-stops, together with a pair of baffles and a flat impact pad in slab caster to improve steel cleanliness and fluid flow phenomenon in a two strand tundish. In the computational work of Sahai and Ahuja (1986) and the experimental work of Singh and Koria (1993), under turbulent flow conditions, the magnitude of the turbulent Reynolds number $N_{Re,t}$, in different tundishes, irrespective to their geometry and dimensions was found to be very similar.

Even though a lot of studies on flow behaviour in tundish have been carried out using physical modelling as well as mathematical modelling, most of the literatures deal with the fluid flow and/or heat transfer analysis for a particular tundish with or without the use of residence time distribution (RTD) curve, very little information is available on mixing and heat transfer analysis for a tundish with the change in the geometrical parameters of the tundish. It is speculated that by changing the geometrical parameters of the tundish (width, height, nozzle distance and their simultaneous change), better mixing may be achieved as compared to that of using the conventional flow control devices like dams and weirs. The use of dams and weirs has also led to the formation of dead volume regions in the leeward sides, which leads to inhomogeneous mixing in the tundish. Fixing up dams and weirs in a tundish being much-involved job poses another difficulty.

In the present work, RTD analysis for mixing as well as heat transfer analysis has been carried out on a single stranded Boat type tundish without use of any flow modifiers. The geometrical parameters are varied for different combinations of width, height and nozzle distances of the tundish. The effect of these geometrical parameters i.e. width, bath height, nozzle distance and their simultaneous change on mixing and thermal behaviour inside the tundish have been analysed. These parametric effects for mixing phenomenon helps to optimize tundish geometrical parameters to achieve better homogenized steel quality in the final cast products. The study of parametric effects can also be useful to achieve better quality of steel with criteria other than mixing like Grade change, Inclusion separation etc. with the continuous casting process.

PHYSICAL DESCRIPTION OF THE PROBLEM AND MATHEMATICAL MODEL

The tundish has the dimensions of length, width and depth being 1000mm, 310mm and 370 mm respectively. The geometry of the tundish is shown in Fig. 2. The size of the inlet and outlet is kept as 20mm x 20mm. Mixing in the tundish is studied by injecting a tracer through the inlet stream for a very short time and then computing the mass concentration of the tracer at the exit of the tundish as a function of time. The objective is to compute the ratio of mixed to dead volume, which is regarded as the main parameters for deciding the effective utilization of the tundish volume and hence mixing in the tundish. The response of the tracer at the outlet helps to compute the ratio of mixed and the dead volume (Jha et al.(2001)). The objective is to compare the temporal variation of the concentration of the tracer for all the cases studied.

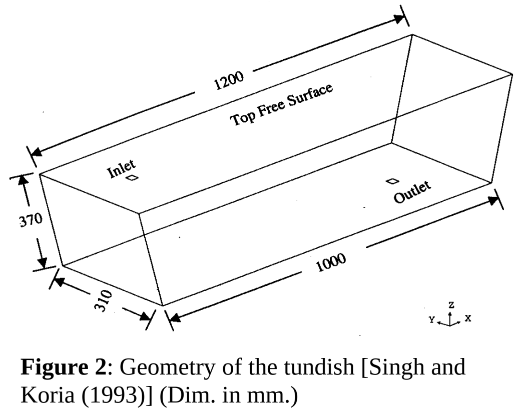

Figure 2: Geometry of the tundish [Singh and Koria (1993)] (Dim. in mm.)

The flow field in the tundish is computed by solving the mass and momentum conservation equations in a boundary fitted coordinate system along with a set of realistic boundary conditions. The tundish boundary does not conform to a regular Cartesian system; the use of BFC is made to solve all the conservation equations. The species continuity equation is solved in a temporal manner to capture the local variation of the concentration of the tracer in the tundish. The free surface of the liquid in the tundish is considered to be flat and the slag depth is considered to be insignificant. With these two assumptions the flow field is solved with the help of the following equations (Eq. 1 to Eq. 4 in tensor form) for all the differencing schemes. The effect of natural convection is ignored in the tundish because the ratio, $Gr/Re^2 = 0.044 \Delta T$ is much less than unity for all the computed cases, where ΔT, the driving force for natural convection is the temperature difference between the liquid steel at the top free surface of the tundish and the bulk temperature of the liquid. Governing equations are given below.

Continuity:

$$\frac{\partial}{\partial x_i}(\rho U_i) = 0 \tag{1}$$

Momentum:

$$\frac{D(\rho U_i)}{Dt} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left\{\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right\} - \overline{\rho u_i u_j}\right] \tag{2}$$

where $\overline{\rho u_i u_j}$ is the average turbulent stress

Conservation:

$$\frac{\partial}{\partial t}(\rho C) + \frac{\partial}{\partial x_i}(\rho u_i C) = \frac{\partial}{\partial x_i}\left(\frac{\mu_{eff}}{\sigma_c}\frac{\partial C}{\partial x_i}\right) \tag{3}$$

Mean residence time:

$$t_{mean} = \frac{\sum C_i t_i}{\sum C_i}, \quad i = 1, 2, 3....2\tau \tag{4}$$

where, τ = tundish volume/ volumetric flow rate

The 3-D domain of this tundish is divided into 17250 cells, making a finer mesh in the zone of the incoming and outgoing liquid jet in order to visualize in more details the effects of velocity, turbulence and thermal gradients. At inlet nozzle the mean vertical velocity is assumed to be uniform through its cross section and other two perpendicular velocities are assumed to be zero. The turbulent kinetic energy and its dissipation rate are too assumed uniform. The volumetric flow rate of steel at the inlet is 1.55 x 10^{-4} m^3/s (Singh and Koria(1993)). The walls are considered with no slip condition for the fluid flow. The upper surface is assumed as a free surface with zero shear stresses. At the inlet, the velocity is 0.3875 m/sec. Turbulence intensity at inlet is specified as 2%. For solution of the species conservation equation, first the tracer (mass fraction value equal to 1) is injected through inlet for the period of 1 sec., once the steady state is attained after the solution of conservation of mass, momentum and energy equations. After 1 sec, the tracer mass fraction is kept zero and the temporal value of the tracer concentration is simulated for the transient conditions for 2 times the theoretical residence time period of the respective tundishes (Levenspiel (1972)).This injection time of tracer is negligible as compared to the residence time of the fluid particle inside the tundish and so does not alter the flow behaviour. For heat transfer calculation, the boundary conditions include the incoming liquid steel temperature as 1873 K. Heat losses are supposed to be taking place through the walls, bottom and free surface of fluid in the tundish. The heat fluxes taken are 2.3 kW/m^2, 3.2 kW/m^2 from the vertical longitudinal walls, and 3.8 kW/m^2 for the inclined transverse walls. The shell conduction through the walls is also considered with thickness of the walls as 10 mm. Heat flux for the free surface is taken as 15 kW/m^2. Physical properties of steel employed in simulation are Viscosity = 0.005 Pa s, density = 7000 kg/m^3, specific heat capacity = 750 J/kg and thermal conductivity of 41 W/m K.

SOLUTION METHODOLOGY

The set of partial differential equations 1 to 5 are solved with the help of the above boundary conditions numerically in a finite volume technique using the education version of the CFD software FLUENT (2003). The steady state velocity field thus obtained for all the cases is used for solving the species concentration Eq. 6. The partial differential equations are integrated over a control volume to find out the fluxes (of mass and momentum as well as that of the tracer) through all the faces, and the flux balance is made over all the control volumes, which yield a set of linear algebraic equations. The set of algebraic equations is solved by the tri-diagonal matrix (TDM) method for momentum and by a whole field solver, taking one from the family of conjugate gradients for the pressure correction equation. The species continuity equation is solved at each and every time step using the TDM matrix method once the steady state solution for the momentum equations is obtained. The solutions are said to have converged when the whole field normalized residuals for each of the velocity components and mass fall below unity. A false time step relaxation of 0.5 is used for all the variables for faster convergence. After the computation of the velocity field the solution for the species continuity equation is initiated in a transient manner. From the temporal variation of concentration the actual mean residence time and all other times are found out by simple integration (Eq. 6) after which the ratio of mixed to dead volume can be found out.

RESULTS & DISCUSSION

The flow field and the temperature profile in the tundish are obtained by solving the Navier-Stokes equations numerically for all the cases and then the tracer dispersion is computed by injecting some tracer into the inlet. Before proceeding to the actual computation for observing the effects of geometrical parameters of the tundish two validations of the computational method are presented with the available experimental results, to ensure the idea of the computational grid size from the comparison with the RTD curve.

Singh and Koria (1993) have done an experiment for a bare tundish for a single strand tundish without flow modifiers (dams/weirs etc). With their dimensions the present validation for two tundishes is carried in this project for the velocity field and the concentration field with a grid of 50 x 23 x 15 (*X* x *Y* x *Z*) for the dimensions of 1000 x 310 x 260 tundish. The other tundish of dimensions 1000 x 120 x 260 is changed proportionally in its grid size. The RTD curve obtained from the present computation is shown in Fig. 3 along with the experimental observations of Singh and Koria (1993). It can be seen that the RTD curve has two peaks in the experiment with the 310 mm width but with computational only one peak is obtained; to ascertain this when grid is made finer there was no difference with respect to no. of peaks but the peak and the later portion obtained through the present grid starts deviating from the experimental curve. Because of increase in the computational time and lesser accuracy and the finer grid is discarded. When grid is made coarser at the inlet and outlet regions there is no difference to the present curve but since the smaller sized tundishes are unable to resolve properly the turbulence and velocity gradients with the coarser grid, the present one a bit finer grid is optimized for simulation. With the present grid the 310 mm case RTD is matching with the peak and the later portions of the RTD very closely. Thus the grid selection seems to be validating the experimental curve quite satisfactorily. The short circuiting shown by first portion of the curve in 310 mm by sharp peak is also present in the computed one, can be seen by the decrease in the plug volume for this case, which will be mentioned explicitly when comparison of the geometrical parametric effects are seen.

With the 120 mm width there is matching of the minimum residence time of the computational and the experimental curves but there is a slight shift of the peak and RTD curve towards right as compared to the experimental one with the proportional grid change. This sort of slight mismatch occurs due to change in the proportions since the values number of the elements is in integer. The slope of the later portion of the curve are very close to each other as the curves are going parallel because of slight rightward shift, thus the overall comparison is satisfactorily close. Thus the proportional changes are made according to the validated grid size with the dimensional parametric change in each of the different cases computed in this study.

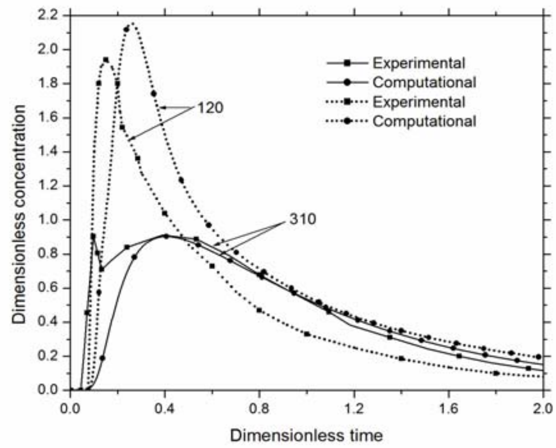

Figure 3: Comparison of computational RTD curve for two tundishes with experimental observations of Singh and Koria

Extensive computations were performed for different parameters such as bath height, width and nozzle distance, which affects the mixing in a tundish, however, only representative results are shown and discussed in the following section.

RTD Analysis

Figure 4 shows the results for RTD curves and volume fractions for the case of nozzle distance of 780 mm, width of 310mm and bath height as 120, 180, 260, and 340 mm. It is found out that RTD curves are close to each other as compared to the other cases of lesser nozzle distances, which shows a little difference in the mixing behaviour. It can also be seen that the mixing ratios are quite close to each other, since all of the three volumes are changing slightly.

RTD curves are having a leftward shift in the peaks with an early start suggesting decrease in the minimum residence time. This is supported by the values of the least plug volumes from table 1 for this width. This phenomenon is called short circuiting of the wider tundishes. This behaviour occurs due to decrease in the resistance to the flow motion by widening of the tundish walls. For this width there is a significant increase in the mixed volume fraction as compared to that of the previous width cases of bath height variation can be seen from the table 1 values. This is due to lowering of the peaks to quite an extent suggesting lesser amount of tracer coming from the outlet, resulting increase in the average residence time of the tracer. In this case too, the mixing ratio is

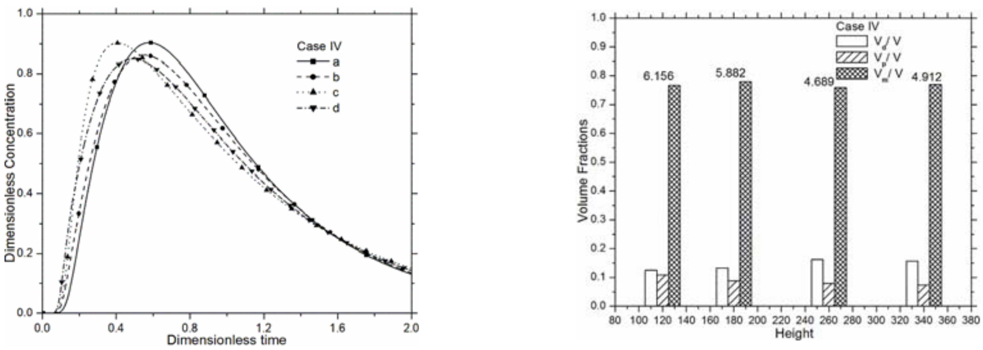

Figure 4: (a) RTD curves for different bath height of tundish and (b) Volume fractions for different bath height of tundish, Case {a, b, c, d}

maximum for minimum height case i.e. case {a}. In all of the cases discussed for the variation of the bath height, it is observed that the value of the plug volume is also maximum for the cases of maximum ratios of mixed to dead volume.

All dimensions in mm			Volume Fractions	
Width	Bath Height	V_d/ V	V_p/ V	V_m/ V
		Dead	Plug	Mixed
72	120	0.23333	0.16670	0.60000
	180	0.38202	0.13559	0.48239
	260	0.41055	0.03876	0.55039
	340	0.40828	0.02367	0.56805
120	120	0.06061	0.29293	0.64646
	180	0.13423	0.20134	0.66443
	260	0.29767	0.08372	0.61861
	340	0.32978	0.04965	0.62057
167	120	0.05797	0.22464	0.71739
	180	0.06731	0.18750	0.74519
	260	0.23000	0.08333	0.68667
	340	0.28571	0.06122	0.65307
310	120	0.12451	0.10895	0.76654
	180	0.13247	0.08831	0.77922
	260	0.16187	0.07914	0.75900
	340	0.15659	0.07418	0.76923

Table 1: Different volume fractions and ratios of the tundishes for variation of bath height

This suggests the increase in the plug volume fraction assists the mixing capability of the tundish. The 120 mm bath height is found to better for mixing, for all of the tundish width with the variation of the bath height.

For the cases in which the width is varied, it is observed that 72 mm width tundish produces a strong short circuited flow for all of the considered bath heights. With the wider tundish of size 310 mm there is again presence short circuited flow for a certain small period of time which is the short circuiting of the wider tundishes due to reduction in the side wall resistance to flow motion. The medium i.e. 167 mm and wider tundish i.e. 310 mm, found better for mixing than the narrower tundishes.

It is also observed that the effect of changing nozzle distance on the RTD curves is smaller as compared to the width and the bath height change. It is found that the shortest nozzle distance of 580 mm is detrimental for mixing as the dead volume fraction is increasing. With the smallest dead volume fraction the 880 mm nozzle distance is found to be better as compared to all other cases of nozzle distance.

Flow field analysis

It can be seen from figure 5, the recirculation is almost absent with widening of the tundish to this width. A little portion of the flow in {c} and {d} is observed to be with the flow reversal near inlet region. The vectors are seen to be with higher magnitudes and in the forward direction in case {a}, {b} and {d}, which increases the mixed volume fraction; as compared to {c}, where stagnant conditions are seen to be present with lower velocities. This is supported by the values of the dead and mixed volume fraction in table 1 for case {c}. It is also found that with increase in the bath height the reversing and recirculating flow regions inside the tundish increase, which assist formation of dead volumes. The forward motion of the flow towards outlet from top free surface in the tundish increases mixed volume fraction to increase the mixing capability. The stagnant regions near the right side of the outlet, top surface due to retardation to the forward moving flow from counter-flow, occurred due to recirculating flow as well as the centre of vortexes formed due to recirculation, are found as the main dead volume causing regions.

Heat transfer analysis

In the following discussion (figure 6) temperature contours are shown on a vertical plane passing through the inlet and outlet and also at the top surface of the tundish.
The continuous constant heat input of 1873 K of steel is supplied and the heat transfer behaviour of tundish for steady state conditions is analysed. The locations of the more cooled regions of bluish colour are seen more towards the outlet side suggesting more forward direction flow and reduction of recirculating and flow reversal, which assists the mixing capability. The dead regions are also seen reduced as compared to lesser width cases. The outlet temperature of the melt is seen reduced with the increase in the bath height as in previous cases due to increase in the heat transfer area. More cooling is also observed height wise with the increase in the bath height

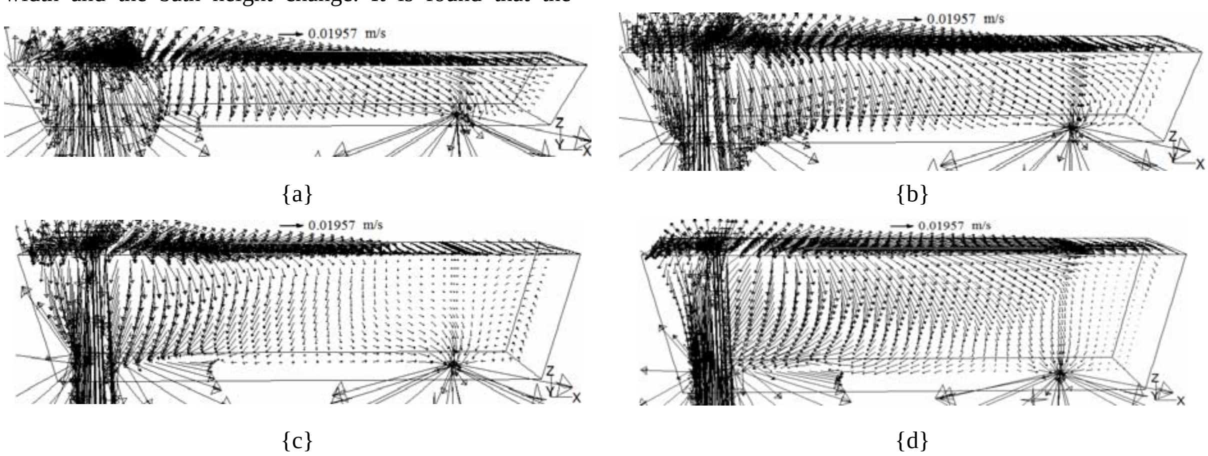

Figure 5: Velocity vectors at a vertical plane passing through the inlet and outlet as well as on the top free surface for different bath heights of the tundish. (a) 120 mm (b) 180 mm (c) 260 mm (d) 320 mm

suggesting increase in the dead volume fraction. It is also observed that with the increase in the bath height, bluish coloured cooler regions shift towards the top free surface and inlet side with the increase in the bath height, due to recirculating and reversing flow.

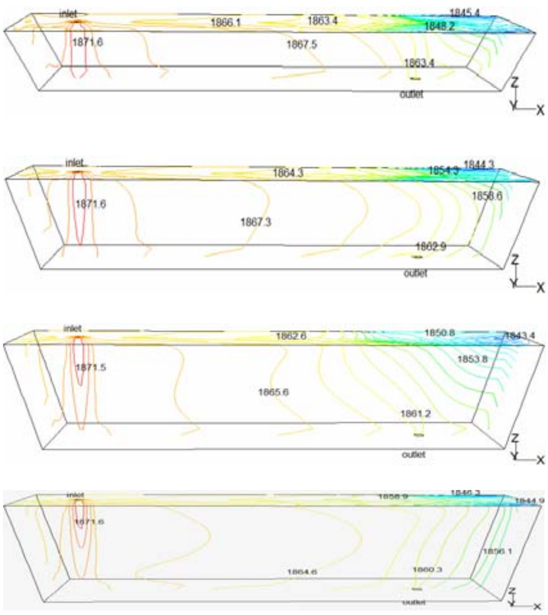

Figure 6: Temperature contours for different cases of bath heights (as in figure 5)

It is also observed that due to the increase in heat transfer rates, the outlet temperature of the steel decreases with the increase in bath height, but as the drop in the temperature does not increase in the same effect, the heat transfer from the tundish is more governed by the nature of flow of steel and locations of the solidifying dead regions inside the tundish than the overall heat transfer rates.

CONCLUSIONS

Fluid flow in steady as well as unsteady state and thermal analysis of molten steel flow in the tundish is carried out for a single strand tundish. The flow dynamics and heat transfer in the tundish is analysed by presenting the velocity field, Residence time distribution (RTD) curves and the temperature profiles by changing the geometrical parameters simultaneously such as width, bath height and the nozzle distance of the tundish. The ratio of mixed to dead volume, which indicate the mixing capability of a tundish, is calculated in each case. The validation of the computational work with the experimental curves of the RTD analysis ensures the computational grid size for the simulation. From the variation of the bath height with the RTD curves, it has been found that with the increase in the bath height the minimum residence time of the tundish reduces significantly. It is also found that the increase in the dead volume fraction proves detrimental for mixing, and this fraction is found more sensitive than the other two volumes to find mixing capability hence it is of importance to reduce this stagnant portion as far as possible

REFERENCES

CHAKRABORTY, S., and SAHAI, Y., (1991), “Role of near wall node location on the prediction of melt flow and residence time distribution in tundishes by mathematical modelling”, *Metallurgical Transactions B*, **22**, 429-436.

FLUENT User’s Guide - Release 6.1, (2003) Fluent Inc.

JHA, P., DASH, S. K., and KUMAR, S., (2001), “Fluid Flow and Mixing in a Six-Strand Billet Caster Tundish: A Parametric Study”, *ISIJ Int*, **41**, 1437-1446.

KOVAC, P., KIJAC, J., MASEK, V., MAREK, P., KALMAR, P., and MICHALEK, K., (2003), “Steel Cleanliness Improvement though Tundish configuration Optimizing”, *METALURGICA* **42**, 249-255.

LEVENSPIEL, O., (1972), Chemical reaction engineering, John Wiley and Sons Inc., New York.

LOPEZ-RAMIREZ, S., MORALES, R. D., and SERRANO, J. A. R., (2000), “Numerical Simulation Of The Effects of Buoyancy Forces and Flow Control Devices on Fluid Flow And Heat Transfer Phenomena of Liquid Steel in a Tundish”, *Numerical Heat Transfer, Part A*, **37**, 6-86.

SAHAI, Y., and AHUJA, R., (1986), “Fluid flow and mixing of melt in steelmaking tundishes”, *Ironmaking and Steelmaking*, **13,** 241-247.

SINGH, S., and KORIA, S. C., (1993), “Model study of the Dynamics of Flow of Steel Melt in the Tundish”, *ISIJ International*, **33,** 1228-1237.

XINTIAN, L., YAOHE, Z., BAOLU, S., and WEIMING, J., (1992), “ Flow behaviour and filtration of steel melt in continuous casting tundish”, *Ironmaking Steelmaking*, **19**, 221-225.