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Optimization of flow control devices to minimize the grade mixing in steelmaking tundish[†]

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Abstract

The minimization of grade intermixing in a tundish is one of the import concern of steelmakers. Different design and operating parameters of the tundish, as well as flow control devices (FCDs), has been used in last decade by researchers to modify the flow characteristics of melt in the tundish. In the present work, the three-dimensional numerical investigations have been carried out to optimise the design of FCDs in multi-strand tundish by using response surface methodology. The interaction of design parameters i.e., shroud depth, advanced pouring box (APB) wall angle, dam height and dam position has been studied by the response surface plots. An effort has been made to quantify the impact of APB angle and shroud depth. Moreover, these two FCDs have important implications in future for efficient inclusion removal. The quantification of intermixed grade steel in tundish has been made at each strand. Further, average output from all strand has been analyzed and the optimum design of FCDs has been suggested. An important finding from this study is that some FCDs have an adverse impact on mixing in the far zone of the tundish.

Keywords: Advanced pouring box; CFD; Intermixing; RSM; Tundish

1. Introduction

The minimization of scrap and third grade intermixed steel is the basic need of steelmakers. This helps in attaining high yield during sequential casting. The high-grade steel production through continuous casting has become global trend [1]. The separation and quantification of intermixed grade steel in tundish is the prime focus of steel producers [2, 3]. Various methods and measures have been opted by metallurgist to overcome the formation of intermixed grade steel in steelmaking tundish. These methods include the use of flow modifiers, grade separator, and change of tundish etc. However, the use of flow modifiers is seen economical in continuous operations. It has been noted from the literature that the operating parameters and flow control devices (FCDs) have a significant impact on the grade intermixing in tundish during ladle change over [4-8]. Numerical and physical modeling experiments are used by researchers to investigate the melt flow phenomenon [9-13]. Kim et al. [14] carried a numerical investigation of flow modifiers in a steelmaking tundish and it was observed that the flow modifiers improve the average residence times. The optimization study of flow control devices for a multi-strand billet caster tundish was carried out by He et al. [15] and it was concluded that the by the use of optimum design flow characteristics improves at each strand. Warzecha et al. [6] used different measurement techniques to identify the intermixed zone in the tundish. The different design of flow control devices has been studied by Cwudziński [16]. The mixing characteristics and Buoyancy number (Bu) have been studied for isothermal and non-isothermal conditions. In addition to this, a mathematical model was developed to analyze the effects of non-isothermal conditions and flow-control device on steel quality by Chatterjee and Chattopadhyay [17]. The alterations in melt flow characteristic were comprehensively studied under isothermal step-up and step-down conditions. Their work clearly identifies the contribution of FCDs and further effect of Buoyancy led flows were studied in different zones of the tundish. Liu et al. [18] carried water modeling experiments to analyze the effect of advanced pouring box and weirs on fluid flow. It was concluded that the FCDs have a great effect on the flow field and the inclusion separation.

An industrial tundish uses various types of FCDs to obtain the desired fluid flow behavior and enhancing the effectiveness of tundish [19, 20]. These FCDs includes advanced pouring box (APB), dam, weir, and baffle etc. A proper arrangement of these FCDs can lead to desired changes in tundish metallurgy. There can be numerous combinations of FCD's dimensions and positions which should be tested to find the optimum position and dimension for getting minimum inter-

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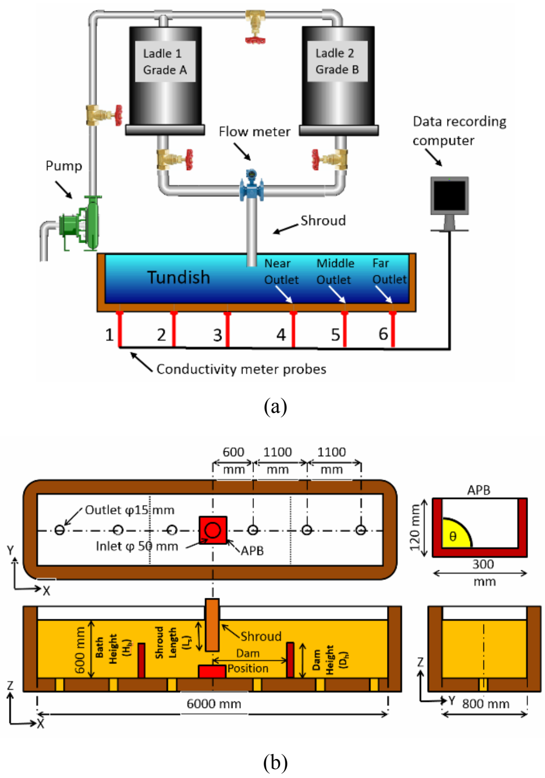

Fig. 1. (a) Schematic diagram of the experimental setup; (b) dimensions and locations of FCDs in a six-strand billet caster tundish.

mixed steel from the tundish. Keeping this in mind, a parametric study has been carried out on a six strand billet caster tundish to optimise the designs of the tundish and its furniture in order to minimise the mixing of different grades. In the present study, a novel APB has been used which has inclined internal surfaces. The dam height and positions have been widely used as a convenient tool to minimize the grade mixing. Until now, little importance has been given to APB wall inclination angle and shroud depth in tundish for grade mixing study. In the present work, an effort has been made to quantify the impact of APB angle and shroud depth. Moreover, these two FCDs have important implications in future for efficient inclusion entrapment. Further, the depth of ladle-shroud in the tundish, wall inclination angle of APB, the height of dam and position of the dam in tundish have been considered for minimising the grade intermixing in the tundish.

2. Experiment

Fig. 1 shows the schematic diagram and detailed dimensions of full-scale billet caster tundish and advanced poring box. The six strand tundish have an advanced pouring box located below the shroud and it has also two dams installed between outlet 1 and outlet 2. The experiment has been carried out on 1/4th scale tundish in the laboratory to validate the numerical model. The water which exhibits excellent dynamic behavior to mimic the molten steel flow was considered as a fluid medium for experiments. At the beginning of the experiment, tundish was supplied with normal water under steady-state operating conditions. To understand the mixing behavior of tundish, another source of homogenized salt concentrated water (salt and colored dye) was opened instead of previous one at steady state operating condition. The homogenized salt concentrated water has more electrical conductivity compared with the normal water. The homogenized concentrated water starts mixing with the old water and subsequently increases the overall conductivity of remaining old water in the tundish. Each outlet of tundish was connected by conductivity meter which measures and records the instantaneous conductivity of the fluid. Further, a graph known as F-curve has been shown in Fig. 2 was plotted against change in conductivity and the instantaneous time. The F-curve obtained from physical setup has been used to validate the results of numerical simulation. A numerical simulation was carried out on a ¼ scale of tundish to validate CFD model with the experimental results. The results obtained from CFD model was found be in good agreement with the experimental values.

Further, a sample intermixing time for a 0.4-0.8 grade specification has been calculated from F-curve (near outlet) as illustrated in Fig. 2. The grade intermixing time directly correlates to the length of solidified slabs of mixed grade steel. Thus, it has been frequently referred as the intermixed amount in the present article. Table 1 shows the characteristic operating conditions of the full-scale tundish.

3. Numerical modeling

The CFD simulations for single phase were carried out on a full scale six strand tundish. The tundish domain was discretized by 0.8 million elements. The symmetry boundary condition was applied at YZ plane to reduce the computational effort. The grade change was studied at three outlets of the tundish namely near, middle and far outlets. The names of outlets are given on the proximate distance from the inlet. The inlet was considered as velocity inlet having 1.4 m/s velocity and outlet was considered as outflow. Molten steel was considered as fluid medium and the numerical solution was solved on Ansys Fluent software. The steady state velocity field was obtained for all sets of designated experiments. The species continuity equation was solved at each time step. The mixing of two grades of steel was monitored at each outlet. The following governing equations of mass (1) and momentum (2) have been used to model the fluid flow and mixing phenomenon inside the tundish. The equations were solved under the assumption of the isothermal condition.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{U} \right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{U} \right) + \nabla \cdot \left(\rho \vec{U} \vec{U} \right) = -\nabla p + \nabla \cdot \left(\overset{=}{\tau} \right) + \rho \vec{g} \tag{2}$$

where p is the static pressure, $\overset{=}{\tau}$ is the stress tensor and $\rho \vec{g}$

is gravitational body force and external body force.

The new grade steel concentration was quantified as per following equation:

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

For turbulence modeling, two additional scalar transport equations of turbulent kinetic energy (k) and its dissipation rate energy(ε) have been solved:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_m \quad (4)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)$$
$$=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{K}\left(G_k+C_{3\varepsilon}G_b\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}. \quad (5)$$

Further, the turbulent (or eddy) viscosity, μt, is computed by combining k and ε as:

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

where Cμ is a dimensionless constant. Following values of constants for turbulent flows have been adapted from the work of Launder et al. [21].

$C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, C_μ = 0.09, σ_k = 1 and σ_ε = 1.30

The density and viscosity of liquid steel at melting temperature (1808 K) was considered as 7030 kg/m^3 and 0.00637 Kg/m-s, respectively. The initial distribution of kinetic energy and dissipation rate at inlet was approximated as 0.003 m^2/s^2 and 0.009 m^2/s^3, respectively. In addition to this, Reynolds stresses are computed by the following Boussinesq relationship [22]:

$$-\rho\overline{u_i' u_j'}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+u_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij}. \quad (7)$$

4. Geometry optimization methodology

For obtaining the optimum results, all possible combinations of FCDs is to be investigated which may require very large computational time in numerical computation. Hence, mathematical and statistical techniques are required for designing experiments, building models, estimating the effects of process parameters and confirming the optimum condition of the tundish. An attempt has been made to develop more accurate and computationally efficient statistical experimental design approaches for the prediction of the intermixed amount of steel in a six-strand billet caster tundish. The use of experimental design in predicting grades intermixing in tundish can result in a novel design of tundish with FCDs, that have least intermixing of two different grades of steel. For this purpose, optimization study has been carried out by response surface methodology (RSM). The numerical models have been used to obtain the responses for various statistically designed experiments. The RSM based design of experiments is implemented due to its usefulness for accurately predicting output at all possible combinations of parameters. In RSM, the desired response "y_i" and independent inputs variables "z_1, z_2, z_3,... z_n" are quantitatively related by the following equation:

$$y_i=fz_1,z_1,z_1,\ldots z_n\pm\epsilon \quad (8)$$

where f is response function while ϵ is a fitting error. In present work, a quadratic model of y_i for 4 input parameters has been considered. The quadratic model can be given as follows:

$$y_i=b_0+\sum_{i=1}^{4}b_i z_i+\sum_{i=1}^{4}b_{ii}z_i^2+\sum_{i=1}^{4}b_{ij}z_i z_j+\epsilon \quad (9)$$

where b0 is constant, bi, bii and bij, represent the coefficient of linear, quadratic and cross-product terms respectively. y1, y2, y3 and y4 represent the ladle shroud depth, APB wall inclination angle, dam height and dam position, respectively. In the present analysis, central composite design (CCD) technique has been used to design the experiments in order to fit the quadratic model. This technique has been extensively used in building the polynomial response surface models. Over the linear model, the quadratic model likely to be more superior as it offers a better fit at the higher power settings.

5. Design of experiments

The tundish design parameters like depth of ladle-shroud (Ls) in the tundish, wall inclination angle of APB (θ), the height of dam (Dh) and position of the dam in tundish have a major impact on grade mixing. The levels of parameters have been selected from the literature available on the use of flow control devices in the tundish. The best combination of FCDs for the minimization of grade mixing in tundish has been determined by applying a three-level-four-factor CCD in the DesignExpert software. Table 1 shows the characteristic operating condition of the full-scale tundish. Fig. 1 shows the various positions of FCDs in tundish which have been considered in this study. Table 2 shows the variable parameters and its level. The thirty designed CFD simulations for optimising the four individual parameters are shown in Table 3. The five replicate sets of simulation at the center of design were estimated by pure error sum of squares. The replicate responses

Table 1. The characteristic operating condition of full-scale tundish at steady state operating condition.

Characteristic parameters	Full-scale tundish
Inlet velocity	1.4 m/s
Bath height (H_b)	600 mm
Length (L_s)	6000 mm
Theoretical residence time	934 s
Shroud diameter	50 mm
SEN diameter	15 mm
Molten steel density	7020 kg/m^3

Table 2. Variable parameters range.

Variable parameters	Symbol	Levels		
		-1	0	+1
Shroud depth (L_s)	A (= L_s/H_b), %	20	35	50
APB wall angle (θ)	B (θ), °	60	95	130
Dam height (D_h)	C (= D_h/H_b), %	20	35	50
Dam position (mm)	D (distance from origin)	700	850	1000

were assumed equal and error free due to the negligible variation of results obtained from CFD simulation. Fig. 3 illustrates the velocity contours plotted on the middle plane (XZ) of tundish for two different cases of the run. It can be seen here that the velocity profile of fluid is significantly affected by FCDs. Subsequently, it will affect the mixing phenomenon inside the tundish.

6. Result and discussion

6.1 Model fitting and statistical analysis

The grade mixing time or intermixed amount at the near, middle and far outlet was calculated from CFD simulation. The results were investigated for analysis of variance (ANOVA) for fitted RSM quadratic model and ANOVA for each term on the performance characteristics has been calculated. By applying multiple regression analysis on the CFD simulation data, the response variable and test variable were related by second-order polynomial equations. The statistical testing of regression equation of each parameter was checked by F-value. The studied models were found significant. The suitability of the model for the present was confirmed on the

Table 3. Design of experiments and responses.

Standard	Run	Shroud depth (A)	APB angle (B)	Dam height (C)	Dam position (D)	Intermixing time (s)			Average intermixing time (s)
						Near outlet	Middle outlet	Far outlet	
1	25	20	60	0.2	700	2849	3503	3713	3355
2	6	50	60	0.2	700	2538	3060	4000	3199
3	13	20	130	0.2	700	3283	3439	3670	3464
4	12	50	130	0.2	700	3311	3467	3595	3458
5	8	20	60	0.5	700	2712	3327	3532	3190
6	7	50	60	0.5	700	2313	2896	4110	3106
7	16	20	130	0.5	700	3214	3432	3798	3481
8	24	50	130	0.5	700	3336	3634	3960	3643
9	1	20	60	0.2	1000	3217	3960	4113	3763
10	22	50	60	0.2	1000	2674	3251	4254	3393
11	14	20	130	0.2	1000	3305	3472	3899	3559
12	29	50	130	0.2	1000	3259	3400	3738	3466
13	21	20	60	0.5	1000	2929	3639	3716	3428
14	3	50	60	0.5	1000	2625	3049	3926	3200
15	9	20	130	0.5	1000	3264	3332	3798	3465
16	10	50	130	0.5	1000	3318	3336	3747	3467
17	30	20	95	0.35	850	3340	3607	3467	3471
18	28	50	95	0.35	850	2941	3381	3634	3319
19	4	35	60	0.35	850	2690	3476	3782	3316
20	18	35	130	0.35	850	3412	3520	3647	3526
21	2	35	95	0.2	850	3265	3557	3677	3500
22	23	35	95	0.5	850	2997	3348	3521	3289
23	5	35	95	0.35	700	3014	3241	3182	3146
24	11	35	95	0.35	1000	3213	3460	3500	3391
25	15	35	95	0.35	850	3210	3432	3557	3400
26	19	35	95	0.35	850	3210	3432	3557	3400
27	26	35	95	0.35	850	3210	3432	3557	3400
28	20	35	95	0.35	850	3210	3432	3557	3400
29	27	35	95	0.35	850	3210	3432	3557	3400
30	17	35	95	0.35	850	3210	3432	3557	3400

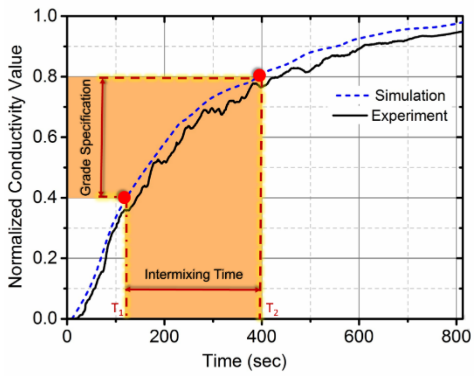

Fig. 2. F-curve (near outlet) obtained from 1/4th scale numerical and experimental model.

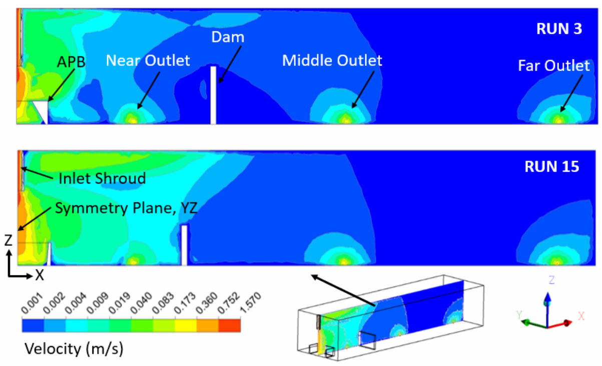

Fig. 3. Velocity contour is shown on the middle plane (XZ) of the tundish for two different combinations of parameters (run 3 & 15).

basis of p-Value of the model which was smaller than 0.0001. The determination coefficient (R2 = 0.9560 to 0.9782 for each response) was close to 1, manifesting that the model could explain more than 95 % of the response value changes. Meanwhile, a low value of the coefficient of the variation (C.V.) in each case has shown a high degree of precision and a good deal of reliability of the CFD results. The result shows the adequacy of the model to represent the relationship between the response and the independent variables. Furthermore, the lack of fit was not presented in terms of F-value due to the significance of all parameters in the model with zero error in CFD results. Adequate precision compared the range of the predicted values at the design points to the average prediction error. A ratio greater than 4 indicated adequate model discrimination. In the present study, the values (A) 20.8, (B) 37.5, (C) 19.8 and (D) 23.2 for each response showed adequate signal.

6.2 Analysis of the response surface of near outlet

The model F-value of 31.98 implied the model was significant. The values of probability (Prob) greater than 'F' and less than 0.05 indicated that the model terms were significant. The significant model terms for this case were A, B, C, D, AB, BC, BD and B2. The three-dimensional response surface plots are shown in Figs. 4(a)-(c) in order to provide a better visualization of the significant parameters which has affected the grade mixing at near outlet. The plots show effects of two parameters on the response at one time while the other two parameters were kept at zero level in all figures. Fig. 4(a) represents the effect of shroud depth and APB wall inclination angle on the intermixed amount. It is seen here that the increase in shroud depth causes a decrease in intermixed amount. In contrast to this, an increase in APB wall inclination angle causes an increase in grade intermixed amount. It can be also noted here that shroud depth has a linear relationship with intermixing time. Fig. 4(b) depicts the interaction of dam

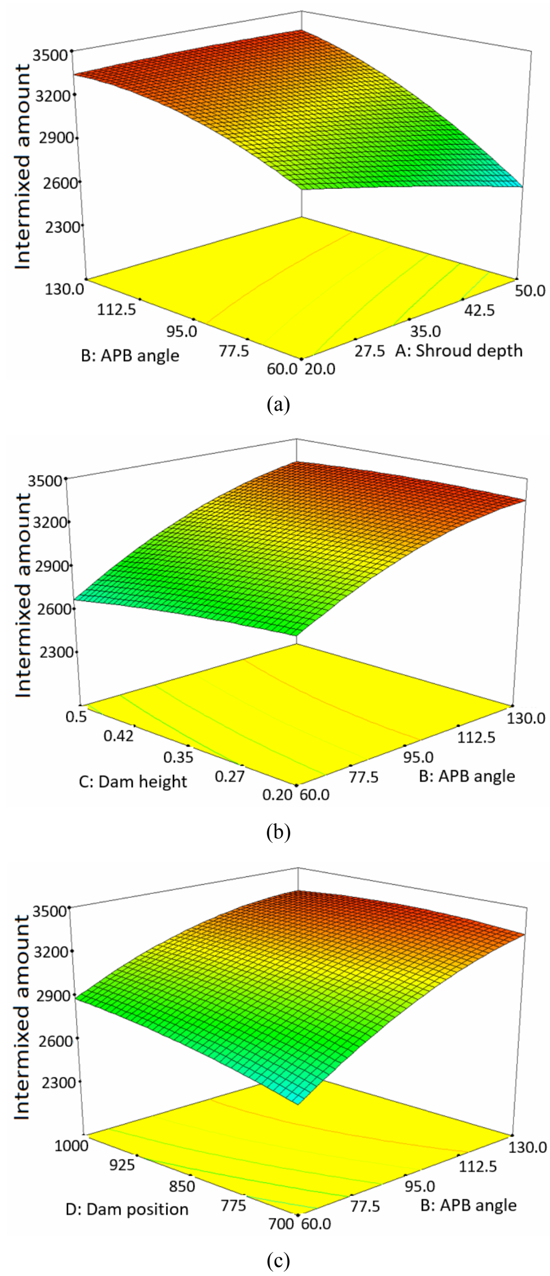

Fig. 4. Response surface showing the interaction of different parameters on the intermixed amount at near outlet.

height and APB angle on grade intermixing. It was observed that the increase in dam height has a minor impact on the mixing as compared to the APB wall inclination angle. Moreover, it is also noted from Fig. 4(c) that the APB angle has a larger influence on the mixing phenomenon inside the tundish. In a conventional tundish, the height and position of the dam in tundish play an important role. However, it is important to mention that the APB angle significantly impacts, and a proper design could minimize the grade mixing.

A second-order quadratic equation (Eq. (10)) was developed for the calculation of intermixed amount at near outlet, based on the interactions of each parameter.

$$\text{Near} = 3181.48-99.89 * A+286.39 * B -55.17 * C+68.56 * D +107.19 * A * B+21.56 * A * C-17.44 * A * D+42.06 * B * C-64.44 * B * D+5.44 * C * D-12.46 * A2-101.96 * B2-21.96 * C2 -39.46 * D2 \quad (10)$$

where A = Shroud depth, B = APB angle, C = Dam height and D = Dam position.

6.3 Analysis of the response surface of the middle outlet

At the middle outlet of the tundish, a similar regression method has been applied. The model and its terms have been found significant. Fig. 5(a) represents the interaction of shroud depth and dam position for the study of grade mixing at the middle outlet. It can be seen that the shift of dam position towards middle outlet has caused an increase in intermixing time, and the afterward position has less impact on the results. Further, it is observed that an increase in shroud depth has reduced the formation of intermixed grade steel at the middle outlet of the tundish. Fig. 5(b) shows the interaction of dam position and APB angle while other two parameters remained constant. It is noted again here that APB angle plays an important role in minimizing the mixing. The grade mixing can be minimized at a suitable low angle of APB design. Similarly, it can be observed from Fig. 5(c) that the dam position has a significant effect on mixing as compared to dam height. Further, a combination of proper dam position and dam height can reduce a considerable amount of mixing in the tundish. A second-order quadratic equation (Eq. (11)) was developed for the calculation of intermixed amount at the middle outlet, based on the interactions of each parameter.

$$\text{Middle} = 3447.68 - 124.28 * A + 48.39 * B - 62.00 * C + 50.00 * D + 145.94 * A * B + 23.81 * A * C - 45.19 * A * D + 51.19 * B * C - 96.56 * B * D - 34.19 * C * D + 30.65 * A2 + 34.65 * B2 - 10.85 * C2 - 112.85 * D2. \quad (11)$$

6.4 Analysis of the response surface of the far outlet

The dispersion of new grade steel takes more time in the far zone of the tundish. Further, the far zone of tundish have less

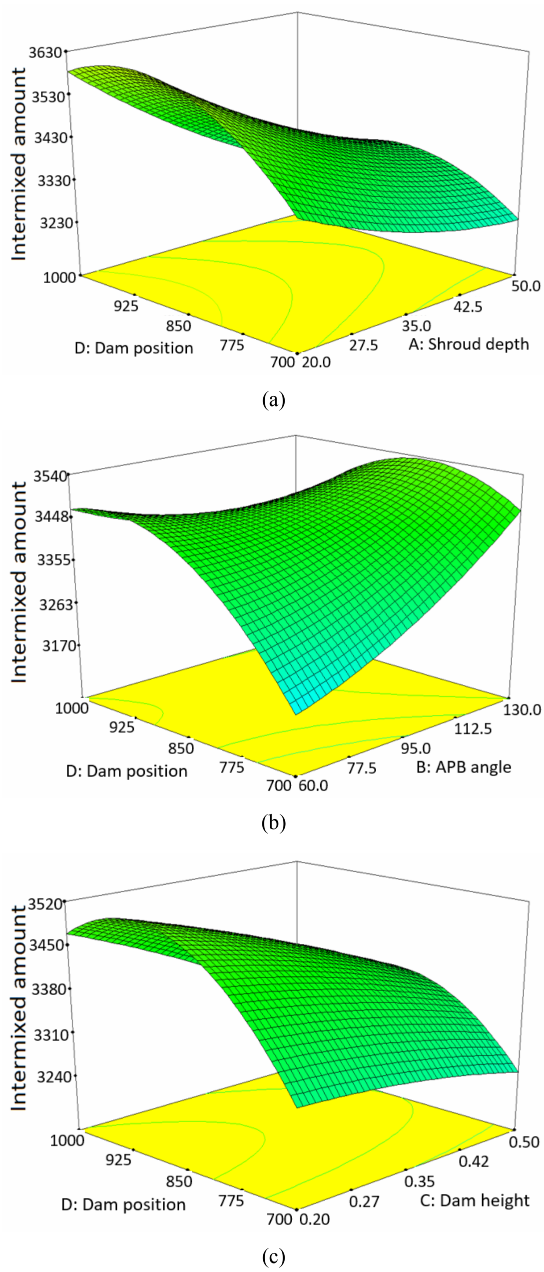

Fig. 5. Response surface showing the interaction of different parameters on the intermixed amount at the middle outlet.

turbulence and presumably, laminar flow exist. The model's F-value of 23.27 implied that the model was significant. The significant model terms for the far outlet are A, B and D. Figs. 6(a) and (b) show the relationship between shroud depth, APB angle and dam position. Contrary to expectation, the low APB angle did not minimize the intermixing at the far outlet of the tundish. Also, it is apparent from Fig. 6(b) that shroud depth has a reverse impact on grade mixing at the far outlet as compared to the near and middle outlets. A consistent correlation has been found between dam height and dam positions on grade mixing. Hence, a comparison of different parameters on three outlets reveals that the APB angle and shroud depth have

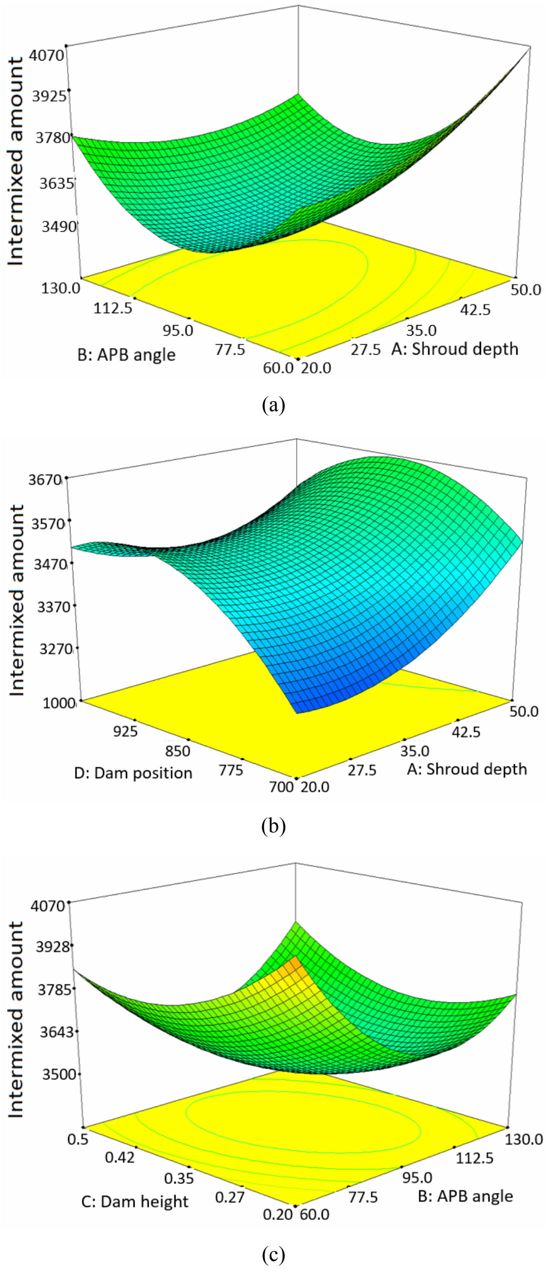

Fig. 6. Response surface showing the interaction of different parameters on the intermixed amount at the far outlet.

a contrary impact at far outlet mixing phenomenon. Thus, average data of three outlets must be analyzed for a better optimization of all parameters with regards to minimizing the intermixing of grades. A second-order quadratic equation (Eq. (12)) was developed for the calculation of intermixed amount at the far outlet, based on the interactions of each parameter.

$$Far = 3512.92 + 69.89 * A - 71.89 * B - 30.61 * C + 62.83 * D - 83.81 * A * B + 44.19 * A * C - 50.81 * A * D + 74.81 * B * C - 30.94 * B * D - 77.44 * C * D + 81.66 * A2 + 245.66 * B2 + 130.16 * C2 - 127.84 * D2. \quad (12)$$

Table 4. Predicted and CFD simulation values for the optimum design.

	Shroud depth (A)	APB angle (B)	Dam height (C)	Dam position (D)	Average intermixed amount		
					Pred.	Sim.	Error (%)
1	38.0	60.0	0.45	700	3094	3149	1.77
2	47.4	61.6	0.40	700	3092	3152	1.89
3	50.0	83.7	0.38	1000	3260	3196	1.97

6.5 Analysis of the response of average output

The analysis of response surface of three outlets reveals that APB angle and shroud depth parameters act contrary at the far outlet of the tundish. Thus, an analysis has been carried out to study the average output of three outlets. The ANOVA model has been found to be significant for average values of all three outlets. Also, the values of probability (Prob) are greater than 'F' and less than 0.0500 indicate the significance of model terms. The significant model terms of the case are A, B, C, D, AB, AC, AD, BC, BD, CD, B2, D2. Fig. 7(a) represents the effect of dam position and shroud depth on the average value of intermixed amount. The data in Fig. 7(a) indicates that the closer dam position has a significant impact on mixing. A similar characteristic of dam position can be observed from Figs. 7(b) and (c). It can be seen here that the shift of dam position towards the middle outlet has increased the intermixed amount. Moreover, APB angle has a significant impact when the dam is placed at 700 mm distance from the origin. Further, it is noted that the effect of dam reduces after the placement of dam more than 900 mm from the origin. Fig. 7(d) shows the relationship curve between dam height and APB angle. A lower amount of mixing can be achieved when a dam height is increased. It is observed that the dam height has major contribution to minimise average output when these two combinations are used. A second-order quadratic equation (Eq. (13)) was developed for the calculation of average intermixed amount, based on the interactions of each parameter.

$$Average = 3380.69 - 51.43 * A + 87.63 * B - 49.26 * C + 60.46 * D + 56.44 * A * B + 29.85 * A * C - 37.81 * A * D + 56.02 * B * C - 63.98 * B * D - 35.40 * C * D + 33.28 * A2 + 59.45 * B2 + 32.45 * C2 - 93.39 * D2. \quad (13)$$

6.6 Validation of the predictive model

The minimization of the intermixed amount from each outlet is one of the main objectives during sequential casting. An optimum design of tundish FCDs has been obtained by the regression model. Table 4 shows the best three optimized dimensions of FCDs. Further, three CFD simulations were carried on the basis of new design to verify the suitability of optimized model. The responses of the proposed optimum design of FCDs in tundish from RSM were compared with the results of new CFD simulations. Table 4 shows that the difference between predicted and simulated values.

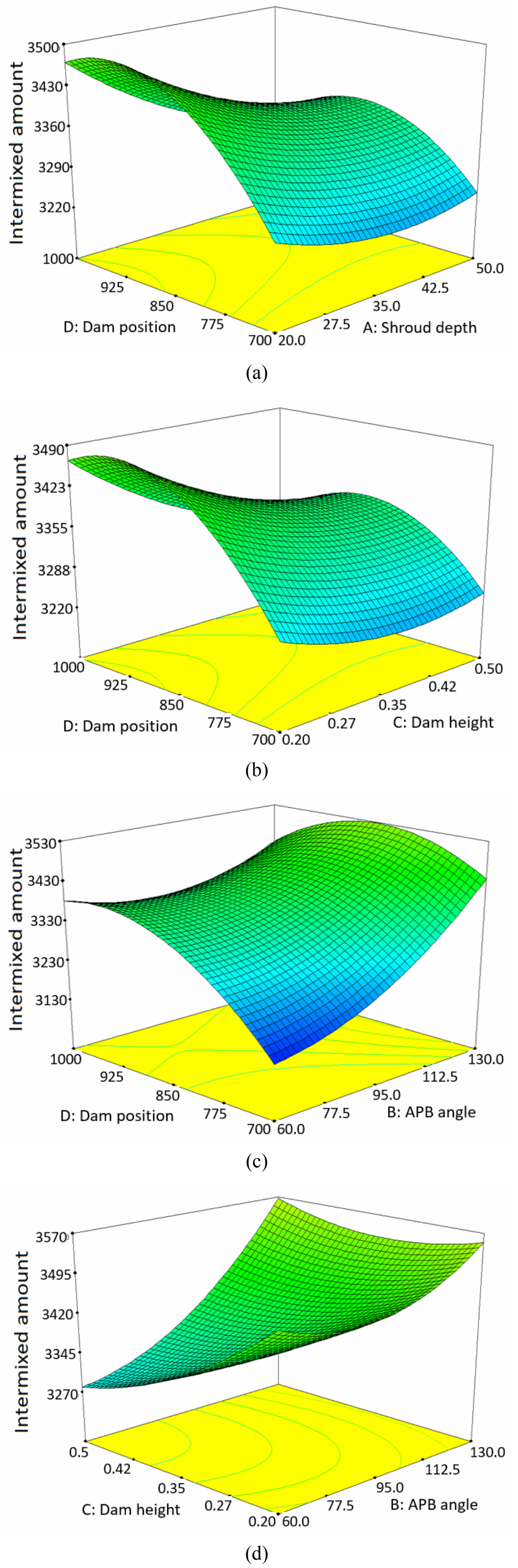

Fig. 7. Response surface showing interaction of different parameters on average intermixed amount.

7. Conclusion

The optimization on the dimensions of FCDs to minimize the intermixing of different grades in tundish has been conducted by using response surface methodology. Four vital parameters such as shroud depth, APB wall inclination angle, dam height and dam position are considered. The novel APB has inclined surface at a various angle and three level and four factorial statistical analyses are implemented using central composite design (CCD). The thirty numerical CFD simulations are performed according to the experimental design. Four responses, in terms of the intermixed amount from each out three and average of all, are monitored. A second-order quadratic equation has been developed for each outlet based on interactions of each parameter. The study has shown that APB angle and shroud depth has a most significant impact on grade mixing phenomenon inside the tundish. An important finding to emerge in this study is that some FCDs have an adverse impact on mixing in the far zone of the tundish. It has been seen that APB angle and shroud depth were capable of minimizing the mixing at the near and middle zone. While the combination of the above-said duo has expounded the mixing phenomenon in the far zone. The research confirms previous findings that other parameters like dam position and dam height are able to control the mixing. Another important finding is that the optimized design of APB angle and shroud depth can replace the use of dams. Further, it is observed that intermixing can be significantly minimized at all outlets by using proper values of APB wall inclination angle, dam height, and position. The optimum value of the parameter which resulted into the minimum intermixed amount for this particular design of tundish are found as follows; shroud depth of 38 %, APB angle of 60, dam height of 0.45 and dam position at 700 mm. The present analysis is limited to six-strand billet caster tundish, more research is needed to better understanding of the impact of APB angle and shroud depth in single strand tundish. The impact of novel ABP angle can be also explored for inclusion entrapment study in steelmaking tundish.

Nomenclature

p : Pressure (Pa)
ρ : Density of fluid (kg/m^3)
μ : Viscosity of fluid (Pa.s)
μ_t : Turbulent viscosity (Pa.s)
μ_{eff} : Effective viscosity (kg/m-s)
v : Kinematic viscosity of fluid (m^2/s)
k : Turbulent kinetic energy (m^2/s^2)
ε : Turbulence dissipation rate (m^2/s^3)
$C\mu$: Dimensional constant
$\sigma_{k,}\ \sigma_\varepsilon$: Turbulent Prandtl numbers
u : Velocity vector (m/s)
σ_c : Turbulent Schmidt number
G_k : Generation of turbulence kinetic energy
C_ε : Turbulent constant

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