IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
Impact Factor: 7.301
Volume 3, Issue 3, June 2023

Temperature Control in Tundish by Combined Reactor Models for Energy Efficient Processing of Liquid Steel

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Abstract: *Tundish plays an important role for continuous casting of steel by controlling the superheat temperature at the tundish outlet or in the concast mold. Superheat temperature is maintained in a narrow range to achieve quality and productivity, since high superheat leads to slower casting rate and higher segregation, whereas low superheat leads to irregular flow and nozzle blockage. Therefore liquid steel flow and thermal condition must be controlled accurately for smooth and consistent operation. Tundish flow and thermal profile can beobtained by 3D CFD simulation. However, CFD simulations for tundish have high computational time and cannot be used for on-line process control. Therefore flow in tundish is evaluated by combining reactor models like Plug Flow Reactor (PFR), Completely Stirred Tank Reactor (CSTR) and Dead zone. The combined reactor model is compared with experimental and plant data published in literature.*

Keywords: Tundish, Reactor model, Superheat Temperature, Casting rate, Process control

I. INTRODUCTION

During continuous casting of steel, the required temperature and composition is attained in the ladle furnace, however this is only the intermediate temperature and the final temperature control takes place in the tundish, where superheat temperature is maintained at the tundish outlet or concast mold inlet. For sequence casting, liquid steel is supplied by a series of ladles, to the same tundish. The liquid steel is then distributed to the single or multiple casters, known as single strand or multiple strand tundish.

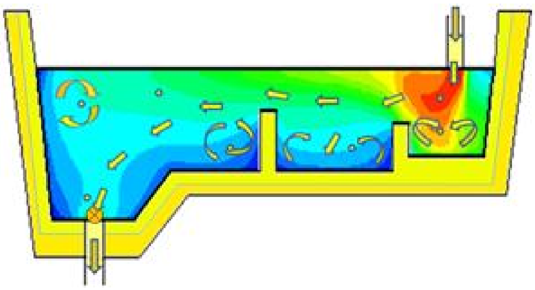

Fig. 1: Single strand Tundish, showing the temperature profile and flow pattern

Tundish process involves various physical phenomena, such as fluid flow, heat transfer, composition and inclusion control, which have been studied extensively by mathematical modelling and simulation [1-2], as well as experimental studies [3-4]. The detailed model based CFD simulation can provide good insight to the process, and used for off-line analysis and design modifications, but the high computation time required for the CFD models restrict them for on-line process control applications.

Therefore important parameters like tundish outlet temperature and composition can be predicted and controlled by developing computationally efficient model, considering the flow in tundish as a combination of reactor flows, such as plug flow reactor (PRF) for laminar flow, completely stirred tank reactor (CSTR) for turbullent flow and dead zone for

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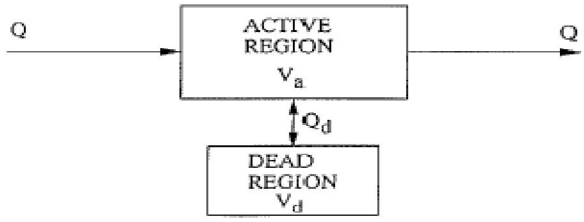
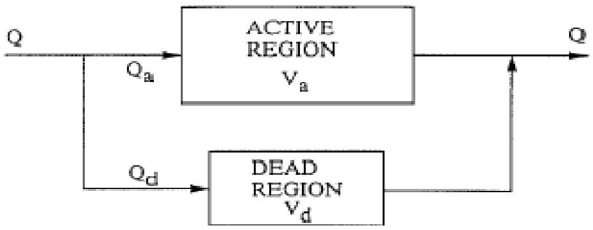
the vortex forming regions [5,6]. The flow and temperature profile in tundish is schematically shown in **Fig. 1**, which shows arrows following a streamline indicating PFR region, and circulating arrows indicating CSTR or dead zone.



(a) Active zone interacting with Dead zone



(b) Parallel flow of Active zone and Dead zone

Fig. 2: Different combination of reactor models for flow in tundish [5].

Residence time distribution in a tundish is studied under various conditions for single, and multi-strand tundish [5-8]. Different types of flow configurations are reported in literature, two most commonly used flow models are shown in **Fig. 2** [5]; the first model shows that all the liquid goes to the active zone, which then interacts with the dead zone, and the second model shows that the flow is divided into two parallel flows, one goes to the active zone and another goes to the dead zone. In this study the second model with parallel flow configuration is considered, and the active zone is again divided into two parallel flows of PFR and CSTR.

II. METHODOLOGY

2.1 Mathematical formulation

The tundish dynamics and fluid flow is represented by a combination of PFR, CSTR, and Dead Zone, which is also a CSTR with twice the residence time. In terms of fluid dynamics CSTR represents turbulent flow and PFR represents laminar flow.

The liquid flow in tundish is considered as combination of laminar flow and turbulent flow with vortex formation and dead zone. Formation of dead zone is due to the vortex formation near the dams and corner positions of the tundish, which is estimated by CSTR reactor with twice the residence time. To simulate the tundish process for liquid flow, temperature and other parameters, partial differential equations for PFR and CSTR have to be solved.

The plug flow is similar to flow through a pipe where some mixing takes place due to diffusion [8]. The 1-Ddynamic equation is solved by finite difference andCranck-Nicholson technique [9], as given below:

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} = D\ \frac{\partial^2 T}{\partial x^2} + S_p T + S_c \qquad (1)$$

The time step is estimated by Courant FriedrichsLewy

(CFL) condition: $dt \leq \frac{dx^2}{2D}$ (2)

In CSTR reactors mixing takes place immediately giving uniform temperature or concentration allover the reactor. The concentration in CSTR depends on volume, liquid flow rate and residence time in the reactor, as given below [10]:

$$V\frac{dT}{dt} = F(T_{in} - T_{out}) - VS_pT_{out} \qquad (3)$$

The inlet flow rate is distributed among the PFR, CSTR and dead zone models to form the combined tundish model. Heat loss in tundish through the refractory wall can be evaluated by 1-D heat transfer equations [11,12].

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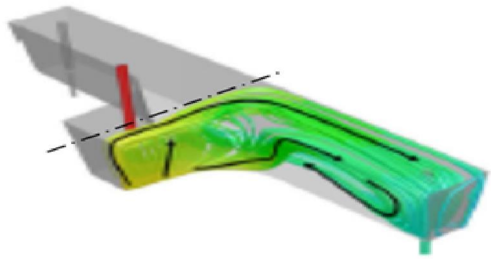
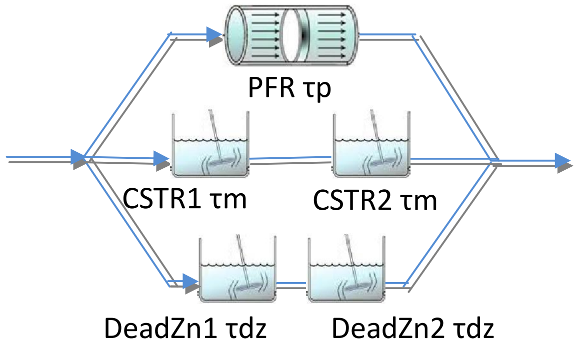
Configuration for Single and Multi Strand Tundish

There are various types of tundish, with single or multi-strand casters. For reducing the modeling effort, the multi strand casters with even number of strands, can be simplified by considering symmetric condition. Therefore single strand tundish and two strand tundish can be modeled by the same reactor flow configuration, as shown in **Fig. 3**.



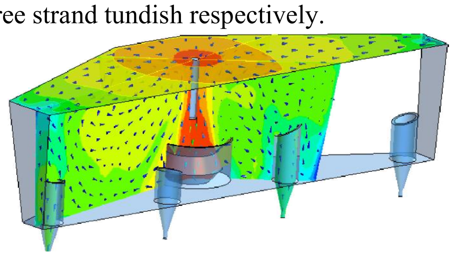
(a) Two strand symmetric tundish



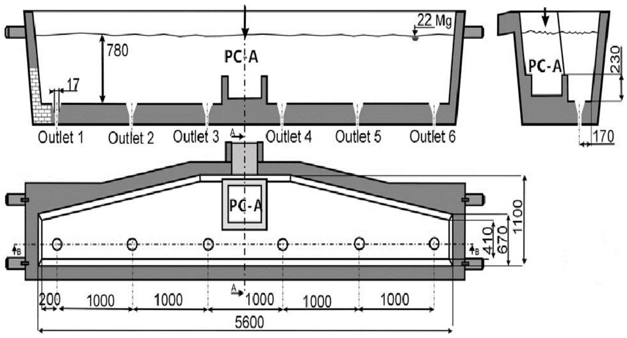
(b) Combined reactor model for single strand tundish

Fig. 3: Model for Single strand or Two strand symmetrictundish.

Similarly, four strand tundish [13] and six strand tundish [14], as shown in **Fig. 4,** are also simplified by considering symmetry, and modeled as two and three strand tundish respectively.



a) Four strand tundish with symmetry



(b) Tundish with Pouring chamber and six strands

Fig. 4: Multistrandtundish with symmetry.

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Multistrand tundish with even number of casters modelled as half the number of caster due to symmetry.The methodology adopted for developing the combined reactor models are:

- Interpretation of the actual process by simplified reactor models
- Computationally efficient process model
- Accuracy and Computational stability under wide range of operating conditions.

III. RESULTS AND DISSCUSSION

The combined results of the PFR, CSTR and dead zone can be obtained by giving a pulse input or a step input of a chemical tracer, and the response at the outlet can be analyzed. The input flow is divided into three parts for PFR, CSTR and dead zone, which can be varied according to the nature of the tundish flow, such that when the flow is smooth or laminar, PFR flow rate is higher, and when it is more turbulent CSTR and dead zone flow rate is higher. By varying the amount of flow in PFR, CSTR and dead zone, we can get different output response as shown in **Fig. 5**, for 30% and 40% plug flow.

The residence time of PFR and CSTR are taken as standard ($\tau = \tau_{PFR} = \tau_{CSTR}$), and the residence time for dead zone is taken as twice the standard residence time ($\tau_{DZ} = 2\tau$).

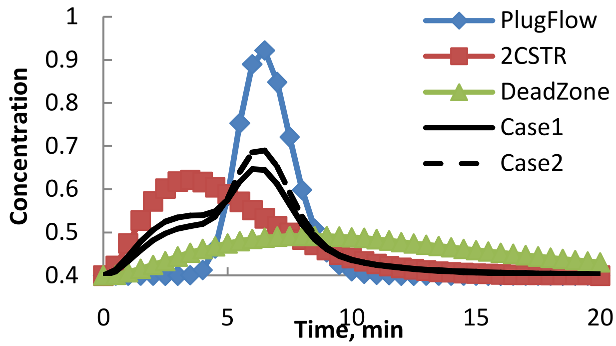

Fig. 5: The result for varying the flow rate of PFR for Case1: 30% and Case2: 40% PFR flow.

The pulse input results in the three casters in a six strand symmetric tundish with a pouring chamber (PC-A) is shown in **Fig. 6.** The three casters have different residence times, however their combined flow rate and residence time is same as the total flow rate and residence time of the tundish.

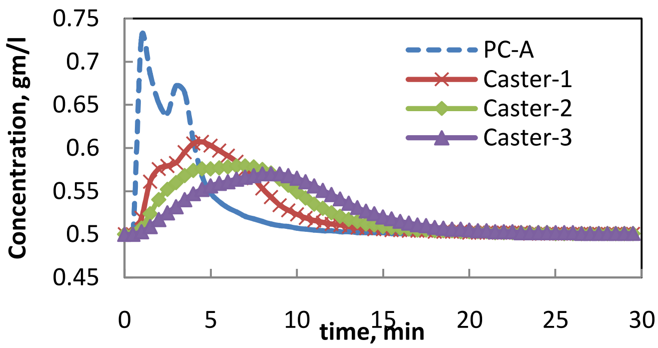

Fig. 6: Results of pouring chamber and the three casters.

The grade change in a tundish can be evaluated by a step input from composition of grade-A to grade-B, as shown in **Fig. 7**, which is similar to the results of Merder et. al [14]. The grade change is very fast in the pouring chamber, however this is only internal value in the tundish, the outlet values in the three casters will actually effect the quality. The grade mix is minimum in caster-1, and maximum in caster-3, which is expected due to the variation in residence times.

DOI: 10.48175/IJARSCT-11477

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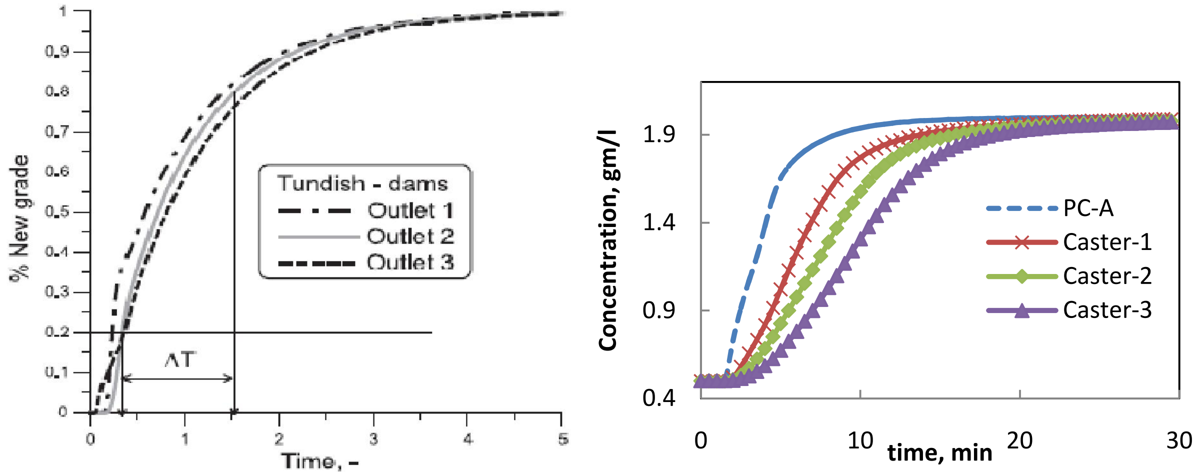

(a) (b)

Fig. 7: Comparison of six strand caster results for (a) Grade change [14], (b) Step input of tracer

Tundish model prediction can be done when the inlet ladle teeming temperature is known [11,12]. This will together predict the superheat temperature in the casters, and the objectives of the models can be summarized as:

- Prediction of Superheat temperature at tundish outlet
- Prediction of mixed grade during Grade change
- Control of quality parameters such as inclusion and nozzle flow blockage

Prediction and control of superheat temperature by the model based system will be an ideal tool for the operators since many of the parameters such as casting speed, segregation of alloying elements etc., depends on the tundish outlet temperature. With this model based prediction and control system the operator will have prior information about the superheat temperature profile, so that he can optimally plan the casting speed and other quality parameters.

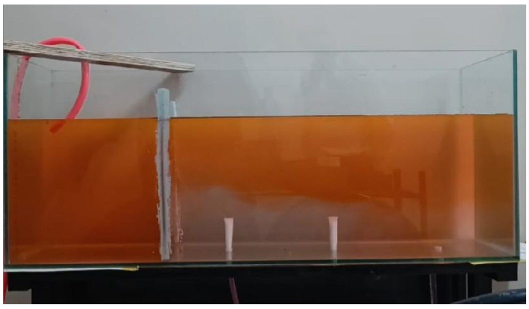

Fig. 8: Water model of single strand tundish with dam.

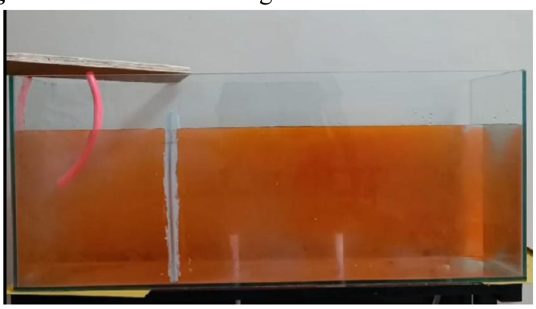

Fig. 9: Water model of single strand tundish without dam.

The flow of liquid steel in Tundish for continuous casting of steel is developed for single and multi-strand tundish, and it is experimentally studied by water flow in a rectangular tank. The experiments were conducted with a flow controlling dam, and another set of experiments without the dam.

The result shows that with the dam the tracer color gets mixed and then comes out through the tundish outlet after 2min 5 seconds for single strand, however without the dam the colored liquid is coming out much faster at about 30 seconds.

Therefore from the results we can observe that there is significant effect of the dam in flow control and mixing. So double chamber configuration as used for the three strand tundish is more suitable. The simplified physics model based on combination of reactor models, have to be fine tunned and customized with the actual tundish data, before it can be used for on-line or off-line analysis.The salient features of thestudy can be summarized as given below:

Water model study of the Tundish flow is done for single and multi strandtundish, with flow control dam and without dam configuration. The time for coloured liquid in outlet is much higher for with dam configuration, and separate chamber like (PC-A) can be used, similar to three strand tundish.

For three strand tundish or six strand symmetric tundish, separate pouring chamber (PC-A) is used, and before the liquid flows through the three strands namely: Caster-1, Caster-2 and Caster-3.

Process model based control system can be developed based on the real-time tundish model for process automation and control.

Funding agency: SPPU's, ASPIRE Research grant scheme.

Concluding Remarks

The computationally efficient reactor model developed for concasttundish is compared with the experimental results published in literature. The comparison shows that the model can capture the trends in tundish outlet. Since this is a model based on simplified physics, it has to be fine tunned and customized for the specific tundish in the steel plant, before it can be used for on-line applications. The important features of the study can be summarized as given below:

The tundish process involving liquid flow, heat transfer and composition mixing is developed by combining the reactor models like PFR, CSTR and dead zone.

The partial differential equations for the reactor models are solved by finite difference and Crank-Nicholson method.

The combined reactor model can be used for predicting the superheat temperature at tundish outlet, for accurate control of casting speed.

The model based system can be used for prediction and control of tundish operations for quality and productivity.

ACKNOWLEDGMENT

The authors would like to thank the management of JSPM's RajarshiShahu College of Engineering, Pune for their constant encouragement and support for this study. We also appreciate the financial support for this project, provided by SavitribaiPhule Pune University (SPPU), under the BCUD's ASPIRE research grant scheme

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