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Tracer Injection Simulations and RTD Analysis for the Flow in 3-Strands Steelmaking Tundish

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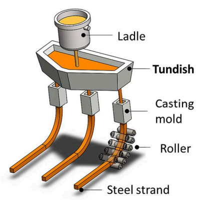
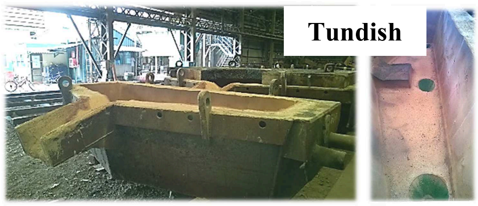
Abstract. Steel cleanliness in the continuous casting process can be improved by the enhancement of inclusion floatation via the flow control in tundish.The aim of this study is to define potential steel flow improvements in the 3-strands tundish of BSI (Bangkok Steel Industry) steelmaking shop. The numerical models of tundish without and with flow modifiers are simulated using the commercial computational fluid dynamics (CFD) software, ANSYS Fluent Workbench 14.0. The simulations of tracer injection using species transport model were performed. Flow characteristics were analyzed by RTD (residence time distribution) curves and the volumes fraction of three types of flow conditions. The results from this reseach shows how the current design of the flow modifiers improves some flow characteristics.

Introduction

With more requirements of steel cleanliness in the modern steelmaking, tundish plays an important role in the continuous casting process in order to minimize the inclusions in the steel products. A typical set-up of continuous casting process is shown in Fig. 1(a). An example of the tundish in the steelwork is shown in Fig. 1(b). Besides a reservoir and a distributor of molten steel, the function of tundish is also a metallurgical reactor. By optimization of the hydrodynamic in a tundish process, non-metallic inclusions, such as Al_2O_3 and SiO_2, can be floated and captured by the slag at the top layer of molten steel if the residence time for the flow from inlet to outlet of tundish is adequate. This can be accomplished by the implementation of flow modifiers which are the fittings of tundish workspace e.g., dams, weirs, turbostop or turbulence inhibitor.





(a) (b)

Fig. 1(a) Diagram of continuous casting process, (b) The 3-strand continuous casting tundish in the steelmaking shop at BSI, Thailand. [1]

A review of the literature on tundish numerical modelling [2] showed that most of researchers had used the k-ε model to model turbulence. With the implementation of the flow modifiers in tundish, the streamlines of molten steel had more opportunity to contact with the steel-slag interface at the top layer which promoted the inclusion seperation [3]. The results from the research [4] showed the example of the tundish modification which prolonged the residence time. Tundish without flow control is inclined to have significant short-circuit flow [5], which results in the increasing of inclusion content in the casting product.

In this study, firstly, the 1-strand tundish model with water flow are numerically simulated in order to validate with the physical water model results from [6]. (The results from physical water model are comparable with molten steel because the kinematic viscosities of them are nearly the

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same, thus making the fluidic behaviour of both fluids similar.) Subsequently, the steady state simulation of the 3-strand tundish with molten steel is performed using the same numerical setup as of the 1-strand tundish simulation. The data of geometry and operating parameters of the 3-strand tundish model are collected from the steelwork at Bangkok Steel Industry Public Co., Ltd. (BSI), Thailand as shown in Fig. 1(b). The flow characteristics such as RTD and the velocity field of molten steel in the 3-strand tundish with and without flow modifiers are investigated. In contrast to the previous study of the main author [1], the simulation of tracer injection using species transport model with transient condition is included in this study and the RTD for each outlet of the 3-strand tundish is analysed seperately.

Methodology

The flows in the tundish working space are simulated using the commercial CFD software ANSYS Fluent Workbench 14.0. The numerical simulations are carried out on the basis of the Reynolds-Averaged Navier-Stokes (RANS) modelling. Fig. 2 shows the geometry and boundary conditions of the 1-strand and 3-strand tundish models. Table 1 shows the details of geometry and parameters.

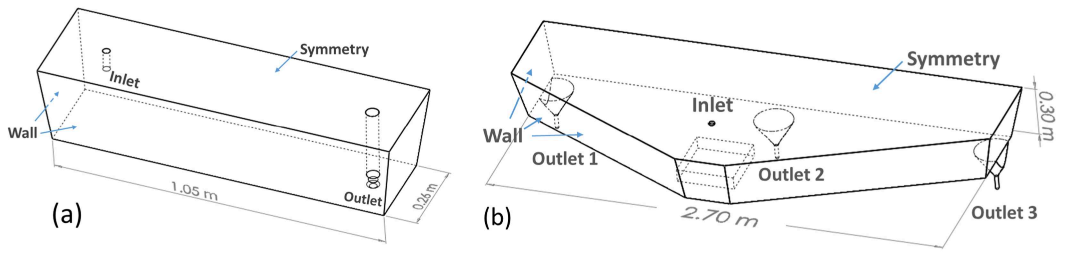

Fig. 2 Geometry and boundary conditions of (a) 1-strand, (b) 3-strand tundish models.

Table 1 Details of geometry and parameters for the tundish models.

	The 1-strand tundish	The 3-strand tundish
Inlet diameter	0.023 m	0.03 m
Outlet diameter	0.023 m	0.014 m
Inlet velocity	2.4 m/s	3.0 m/s
Volume flow rate	1.0 dm^3/s (water)	2.12 dm^3/s (molten steel)

An unstructured computational mesh of 0.5 million cells is used in the meshing process. The realizable k-ε model is used to simulate the turbulent flow. The SIMPLEC algorithm is used in the numerical simulation. The second order scheme is used to provide good accuracy. The simulations are performed under the isothermal condition at 20^{o}C for water and 1556^{o}C for molten steel.

The flow modifiers have been designed and furnished in the 3-strand tundish model. Two dams are set up between 3 outlets and the turbostop is set up around the impact pad under the inlet position as shown in Fig. 6.

In order to optimize the flow control of a tundish process, it is necessary to analyze the flow characteristics of tundish without and with flow modifiers and compare by the RTDs. For this, a tracer which has same properties as molten steel is instantaneous injected for 1 second into the 3-strand tundish model on a steady-state flow field of the model and the concentration variation of the tracer with time is monitored at the 3 outlets. Steady state flow of molten steel is firstly calculated, afterward, a tracer injection is simulated using species transport model with transient mode. After stop injection, the mixed flow of tracer and molten steel is simulated with transient mode for 20 minutes.

For the flow characterization, the first step is to derive the dimensionless C-curve for the tundish. The dimensionless time, ɵ, was calculated as Eq. 1:

$$\theta = \frac{t}{\bar{t}}. \tag{1}$$

where $\bar{t}$ is the theoretical mean residence time as Eq. 2:

$$\bar{t} = \frac{V}{Q}. \tag{2}$$

The dimensionless concentration of strand i (the outflow at outlet i) can be calculated as Eq. 3:

$$C_i = \frac{c_i V}{M}. \tag{3}$$

where V is the total volume of the tundish, c_i is the concentration at the outlet i, and M is the total amount of tracer injected.

The mean residence time of the flow, t_{mean}, is calculated as Eq. 4:

$$t_{mean} = \frac{\int_0^\infty tC(t)dt}{\int_0^\infty C(t)dt}. \tag{4}$$

In the second step, the tundish performance can be classified by separating the flow volumes into three types: the plug flow (V_p), the well-mixed volume (V_m), and the dead volume (V_d) as Eq.5-7:

$$V_p = \frac{1}{2}\left(\theta_{min} + \theta_{peak}\right). \tag{5}$$

$$V_d = 1 - \frac{Q_a}{Q} \times \theta_{mean}. \tag{6}$$

$$V_m = 1 - V_p - V_d. \tag{7}$$

The ratio Q_a/Q is the fractional volumetric flow rate through the active region and is equal to the area under the C-curve between the bounds of $\theta = 0$ and $\theta = 2$. After $\theta = 2$, the data is considered to be the dead volume. The θ_{peak}, θ_{mean} and percentage fractions of flow volumes provide some indication on the metallurgical performance of tundish as a refining vessel. For example, high θ_{peak} and θ_{mean} prevent a short-circuit flow and provide more opportunity for the floatation of inclusions; presence of a relatively large proportion of well-mixed volume indicates adequate mixing in the melt phase and hence better material and heat transport. A large plug flow volume and a small dead flow volume indicate better possibility of inclusion float out [5, 7].

Results and Discussion

The velocity flow field of tundish flow can be illustrated in a 2-D cross section plane at any interested position. Fig. 3 shows the comparison between the velocity flow field from the numerical results of the 1-strand tundish model and that from the experiment result from [6] at the cross section plane 0.2L as shown in Fig. 3(a). Fig. 3(b) shows the CFD simulation result from the current study and Fig. 3(c) shows the experimental result of the water model using the LDA measurement. The flow structure of the two counter-rotating toroidal vortices can be captured from the CFD simulation. The comparison of the flow pattern between the CFD simulation and the experiment results shows good agreement with minor difference. The centers of the two counter-rotating vortices from CFD are a little bit lower than those from experiment.

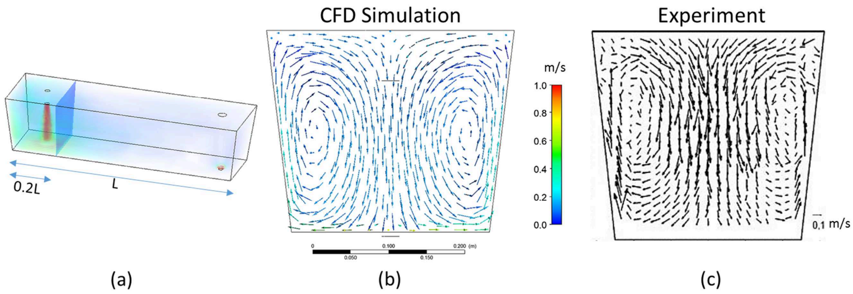

Fig. 3(a) Position of the observed plane, (b) Numerical result from the current study
(c) Experimental result from the article. [6]

From the numerical simulations of the 3-strand tundish, the velocity flow field and residence time curves were determined. Fig. 4 shows the velocity flow field in a cross section plane at the inlet position and the tracer mass fraction after a pulse injection of 1 second. The simulation results of tracer injection in the tundish models without and with flow modifiers are illustrated in Fig. 5 and Fig. 6, respectively. Tracer mass fractions in the molten steel at 1, 3, 10 and 60 seconds after injection are shown with white-blue color scale. From the pictures, it can be seen that the flow of tracer reaches the outlet-2 firstly at around 10 seconds. From the simulation results, the flow of tracer reach outlet-1 and outlet-3 at around 15 seconds for the tundish without flow modifiers and around 26 seconds for the tundish with flow modifiers. This is an indicator that the tundish with the flow modifiers has more opportunity for the floatation of inclusions.

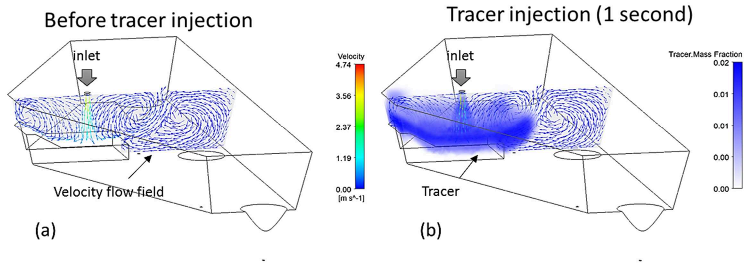

Fig. 4 (a) The steady state velocity flow field on the plane at the inlet position, (b) mass fractions of the tracer (blue color) mixed in the molten steel volume after a pulse injection.

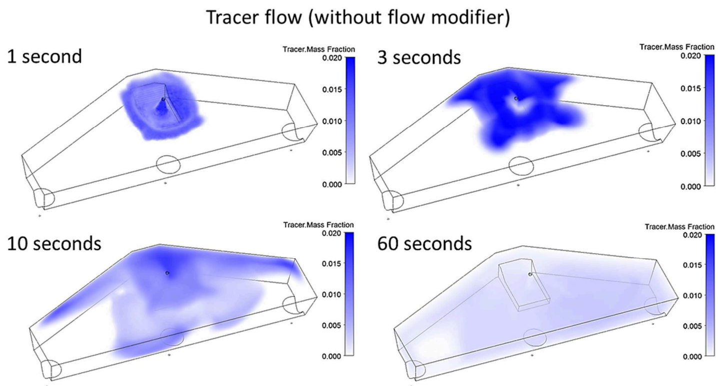

Fig. 5 The mass fraction of the tracer mixed with the molten steel at various time after a pulse injection.

The residence time curves which show the dimensionless concentration (C) of the tracer against time (t) and dimensionless time (θ) at each outlet for the tundish models without and with flow modifiers are represented in Fig. 7. The key indicators for the flow characterization such as t_{peak}, θ_{peak}, t_{mean}, θ_{mean} of the residence time curves, plug volume (V_p), well-mixed volume (V_m) and dead volume (V_d) flows are summarized in Table 2.

From the results shown in Table 2, the time at the peak concentration (t_{peak}) for all outlets are improved after the implementation with flow modifiers. The mean residence time (t_{mean}) of all outlets except outlet-3 are also improved. These are indicators that the prevention of short-circuit flows and the floatation of inclusions are promoted. However, with the current design of the flow modifiers, some of the percentage fractions of plug volumes (V_p), well-mixed volumes (V_m) and dead volumes (V_d) are deteriorated, e.g. the dead (or stagnant) volume for outlet-1 and outlet-2 are increased after the implementation of the flow modifiers. These deteriorated properties would be improved in the future study by the development of the flow modifier design. To compare some numerical results with the available experiment result data, θ_{mean} from this 3-strand tundish model without flow modifier is compare with the θ_{mean} from the 4-strand tundish physical water model without flow modifier [5] both are approximately the same at around 0.7.

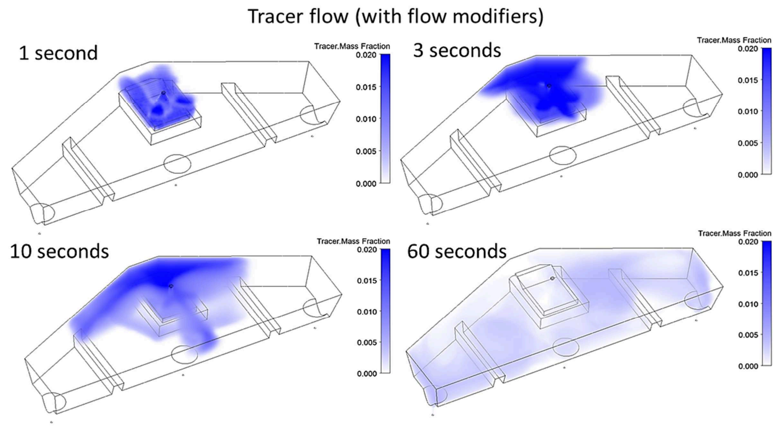

Fig. 6 The mass fraction of the tracer mixed the molten steel at various time after a pulse injection.

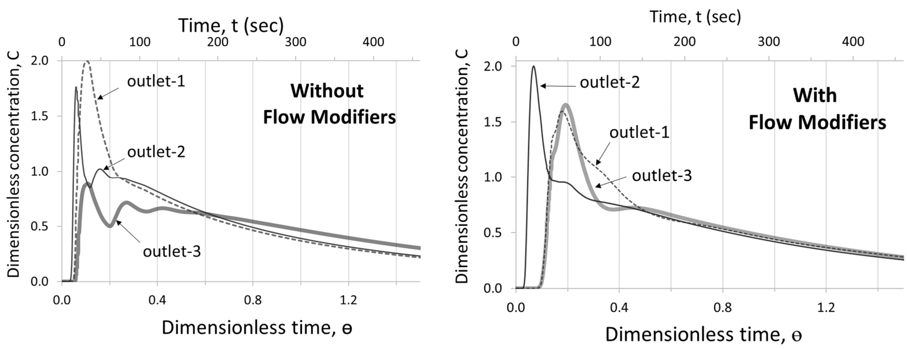

Fig. 7 Residence time distribution for each outlet of the tundish model (left) without flow modifiers and (right) with flow modifiers.

Table 2 Parameters of RTD curves and fraction flow in all outlets of the tundish models.

		t_{peak}	θ_{peak}	t_{mean}	θ_{mean}	V_p	V_m	V_d
		sec	-	sec	-	%	%	%
outlet1	without flow modifier	33	0.11	199	0.65	13	61	26
	with flow modifier	55	0.18	228	0.74	8	54	38
outlet2	without flow modifier	19	0.06	211	0.69	5	63	32
	with flow modifier	21	0.07	214	0.70	5	60	35
outlet3	without flow modifier	33	0.11	255	0.83	14	59	27
	with flow modifier	59	0.19	233	0.76	8	64	27

Conclusions

CFD simulations including species transport model allowed predicting the flow behaviors and tracer injections in the tundish. The CFD simulation and the experiment results of 1-strand tundish model shows good agreement with minor difference. The flows characterized by RTD and 3-types flow volumes separation for each casting outlet of the 3-strand tundish were analyzed. The results show that with the implementation of flow modifiers in the tundish models the short-circuit flows are reduced and the residence time distribution are improved. This mean that the opportunity of the inclusion floatation is increased and would promote the steel cleanliness. With current design of the flow modifiers, some indicators of the flow characterization are descended, e.g. the increasing of dead volume fraction (V_d), therefore, the study in the future will include the improvement of these indicators by the development of the flow modifier design. The future research is also to develop the physical water model in the laboratory scale using tracer injection and measuring device such as electric conductivity meter in order to validate the numerical model of the tundish. The design of water model has been conducted in this study and shown in Fig. 8

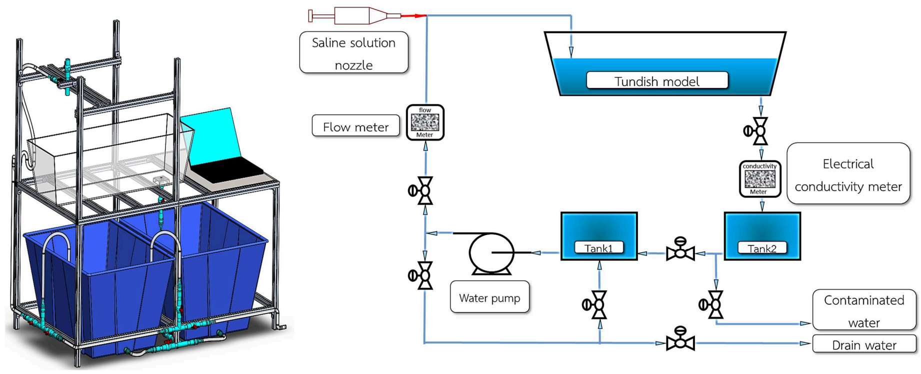

Fig. 8 The design of the laboratory scale physical water model for the future work.

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