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Numerical study of influence of casting speed on fluid flow characteristics in the four strand tundish

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ABSTRACT

Steel maker companies attempt to achieve high production quality and decrease production costs due to high competition of the global steel industry. Steel cleanliness plays a significant role in the steel quality which is the key success factor for the steelmaker. In order to optimize the steel cleanliness in the continuous casting process, flow characteristics were studied to enhance the inclusion removal efficiency in four strand tundish. The purpose of this research is to study the effect of casting speed on the flow characteristics of molten steel inside a four-strand tundish. The investigation was carried out by using the commercial computational fluid dynamic (CFD) software ANSYS 18.2. A 1:3 water model tundish based on process parameters from Millcon Steel PLC were employed in this study. The simulation results were validated with the physical water model. The residence time distribution (RTD) curves were applied to analyze the flow characteristics of the tundish. The results of this study show the different casting speeds have an effect on the flow characteristics inside the tundish. The start point of RTD curve of the flow in the tundish with casting speed of 3.0 m/min is the shortest amongst all casting speeds used (1.7, 2.0, 2.3 and 3.0 m/min). A short time period of the start point of RTD curve increases the chance of inclusion contamination in the casting mould and leads to low quality products. Furthermore, the outlet positions affect the minimum residence time of RTD curves and the tracer concentration directly. The RTD start point of the middle outlet located close to the inlet position is faster than that of the far outlet located far from the inlet. The results obtained from the study contributes to the optimization of productivity and quality of the example plant.

1. Introduction

With high competition of global steel market, many companies attempt to achieve high production quality. Steel cleanliness plays a vital role to optimize the quality of the steel in the continuous casting process [1,2]. In a continuous casting processes, a tundish is the metallurgical vessel that reserves the liquid steel before distributing the molten metal into each mold to solidify in the continuous casting process as shown Fig. 1(a). The flow modifiers such as wier, dams and stopper rods were furnished to increase the cleanliness of liquid steel in the tundish. Fig. 1 (b) show the example of real tundish which furnished the flow modifiers.

Several research studies [3,4] used CFD simulation and physical water model to investigate the flow characteristics and inclusion removal in the tundish. The k-ε model is the most widely used equation model to predict the turbulence phenomena [5]. The residence time distribution (RTD) curve is widely used to analyze flow characteristics in the four strand tundish [6]. Flow modifiers were furnished to study the flow characteristics in order to promote the inclusion removal inside the tundish [7]. In addition to the flow modifiers, the stopper rod could control the feed rate of metal flow, which flows from the inlet to the outlet inside the tundish [8]. In order to maintain the mold constant, the formulation of stopper rods lift was calculated to define the possibility for controlling

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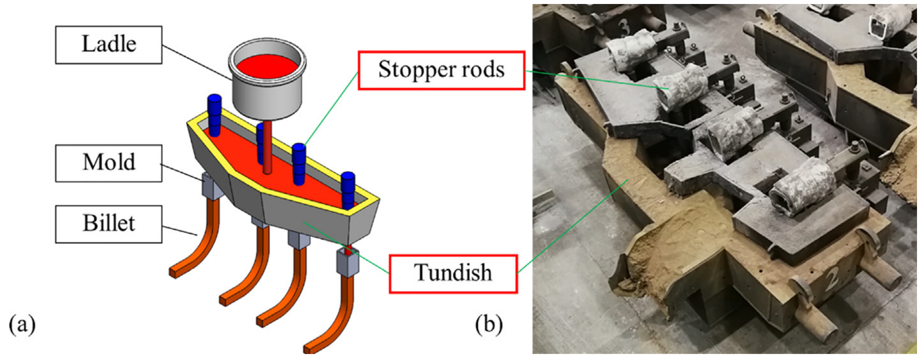

Fig. 1. (a) Schematic of continuous casting process; (b) The example of real tundish at example plant.

the casting speed properly [9]. Moreover, previous research revealed that the variation of casting speed has significant effects inside the tundish such as the reduction of the dead zones in the tundish which results in an increase in steel cleanliness [10]. The RTD curves of the symmetric tundish at the outlets show similar flow patterns as of those located at the opposite position. The results also showed that the outlet located near turbostop has higher chance of inclusion than that of the outlet which is far away from the turbostop in the multi-strand tundish [11].

The purpose of the current research is to investigate the influence of the process parameters on the flow characteristics inside tundish to improve the inclusion removal potential and increase the productivity. This study focuses on controlling flow rates corresponding to the desire casting speeds of fluid flow by adjusting diameter inlet and stopper rods of movement at outlet. The data of geometry and process parameters of 4-strand continuous casting tundish from the example plant was used in the simulation study and the experimental study. The numerical study was carried out by using CFD and experimentally validated with the physical water model. The RTD curve was analyzed in order to explain the flow characteristics of the tundish. The results obtained from this study will be useful to develop the steel cleanliness in the steel industrial.

2. Numerical simulation and physical methodology

2.1. The similarity criteria of water model and prototype model

Froude similarity criterion was used in a reduced-scale water model of tundish. There should be constant ratios between corresponding quantities in the model and in the actual tundish. Therefore, dynamic similarity and geometrical similarity of the water model (Fr_m) which can be described in eqs. (1) and (2) [12]:

$$Fr_m = \left(\frac{V^2}{gL}\right)_m = \left(\frac{V^2}{gL}\right)_p = Fr_p \tag{1}$$

$$\lambda = \frac{L_m}{L_p} = \frac{1}{3} \tag{2}$$

where V is the inlet flow velocity $(m \cdot s^{-1})$, g is the gravitational constant $(m \cdot s^{-2})$, λ is the length scale factor, L is the character dimension (m); subscript p is the original prototype tundish, subscript m is the tundish model of the example plant.

The proportion of flow rate of the water model (Q_m) to the original phototype tundish (Q_p) is

$$\frac{Q_m}{Q_p} = \frac{V_m \pi r_m^2}{V_p \pi r_p^2} = \sqrt{\lambda} \cdot \lambda = \lambda^{2.5} \tag{3}$$

where r is the radius of inlet (m), Form eq.(3), flow rates of the original phototype tundish were calculated to obtain flow rates of water model that corresponds to the desire casting speeds of fluid flow.

2.2. Tundish parameters

The parameters of four-strand tundish of the example plant were applied in this research to investigate the influence of different casting speeds on the flow patterns inside the tundish. A 1:3 scaled tundish model was built by using commercial CAD software as shown Fig. 2 the Dynamic similarity and geometry similarity of the 1:3 tundish and the full-scale tundish model were compared based on the Froude similarity. The Froude similarity criteria were calculated to obtain the reliability of flow rate in the tundish as shown Table 1. Water was used to represent molten steel in this study due to the equivalent of the kinematic viscosity of water and liquid steel at 1600 ◦C. Different flow rates were controlled by the variation of stopper rods and inlet width to obtain the desired casting speeds of fluid flow (1.7, 2.0, 2.3 and 3.0 m/min) as shown in Table 1. The casting speeds were used to investigate the flow characteristics and the effects of inclusions in the tundish. The inlet width and the movement of stopper rod were calculated to use in the simulation and the experimental study.

Steady-state condition is applied in this present study to obtain the equivalent of inlet and outlets flow rates in the 1:3 scaled tundish. Flow rates of inlet and outlet were defined as stable velocity. The variation of stopper rod positions provide desired areas that define the flow rates of the outlet since the stopper rod movement has a significant effect on the flow rates of the outlet. The area of the outlet was configured by stopper rod movement to attain the flow rates that are in accordance with the casting speed in all cases as shown in Fig. 3(a) A turbostop has been employed to optimize flow characteristics [13]. It is a key factor to alleviate the impact zone of tracer injection on the tundish bottom. Thus, it was furnished inside tundish in this study to obtain the optimization of flow characteristics as shown in Fig. 3(b)

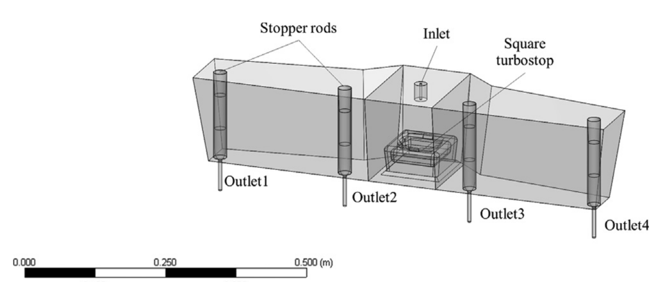

Fig. 2. Geometry of four strand tundish showing all components of tundish.

Table 1
Flow rates of the full-scale tundish (Q_p) and the 1:3 scaled water model (Q_m) corresponding to four different casting speeds.

Cases	Full scale tundish (liter/min)		1:3 scale tundish (liter/min)		Casting speed (m/min)
	$Q_{p,\ inlet}$	$Q_{p,\ outlet}$	$Q_{m,\ inlet}$	$Q_{m,\ outlet}$	
A	162.0	40.5	10.4	2.6	1.7
B	190.6	47.7	12.2	3.1	2.0
C	219.2	54.8	14.1	3.5	2.3
D	285.9	71.5	18.3	4.6	3.0

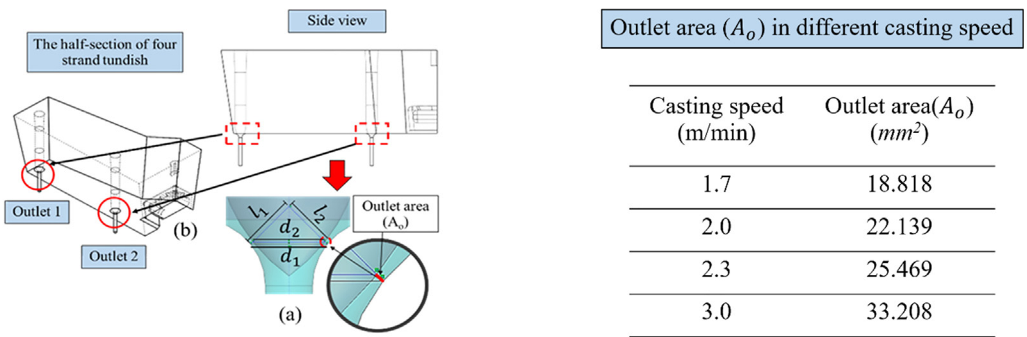

Fig. 3. (a) outlet's positions and the calculation of stopper rod lift in different casting speed; (b) the calculation of outlet area.

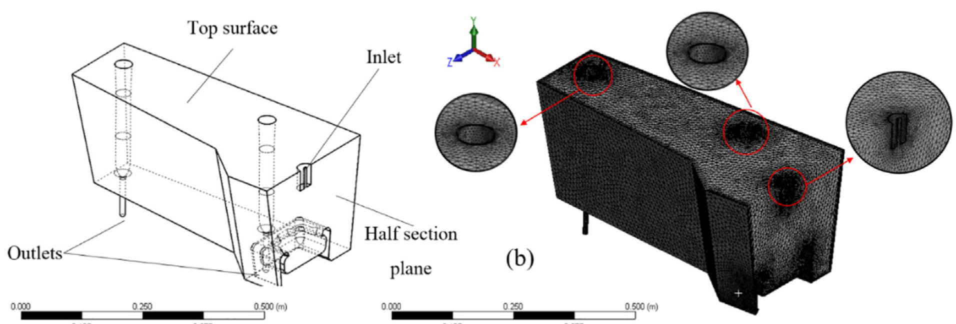

Fig. 4. (a) Boundary conditions; (b) the computational mesh in the half-section tundish.

As shown in Table 1, the different flow rates of the 1:3 scaled water model (Q_m) were calculated to obtain desired casting speeds (Case A-D). The casting speeds of 1.7, 2.0, 2.3 and 3.0 m/min were applied to investigate the flow characteristics inside the tundish.

2.3. Numerical simulation setup

The half-section of four-strand tundish with fixed outlet width and stopper rods lift were simulated in the commercial software ANSYS 18.2 Fluent. The boundary conditions at the inlet, outlets, top surface and half section plane were defined as the constant velocity, outflow, symmetry and symmetry respectively as shown in Fig. 4(a). The computational mesh of 12 million elements were used in the CFD simulation to obtain the precise results. Inlet, outlets, stopper rods and turbostop zones are performed with different mesh resolutions as shown in Fig. 4 (b). The simulation was performed under the following assumptions: 1) isothermal condition, 2) 3-D steady-state, and 3) transient mode during tracer injection.

In this research, the numerical simulation of the tundish was carried out based on Reynolds-Averaged Navier-Stokes (RANS) modeling. The k-ε model [14,15] has been applied to predict the turbulence flow pattern in the tundish. The flow characteristics of turbulent flow phenomena was simulated by the realizable k-ε model and the SIMPLEC algorithm. The second order scheme is used in the simulation to obtain accurate results. The injection of tracer was used to observe the flow characteristics in the tundish. The species transport model was used to explain the variation of tracer concentration inside the tundish. The tracer with the same properties as the liquid steel was injected for 1 s into four strand tundish on the steady state and transient conditions. The injected tracer was recorded for 20 min.

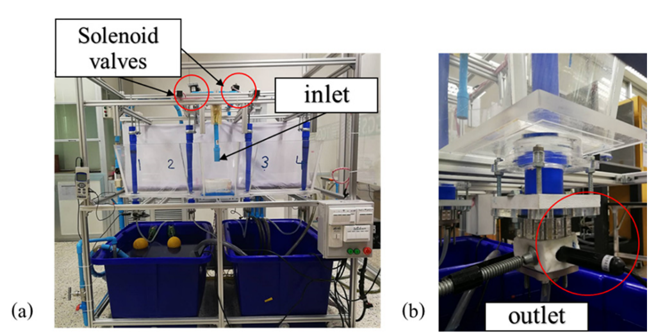

Fig. 5. (a) The physical water model and the solenoid valve; (b) the detection of conductivity.

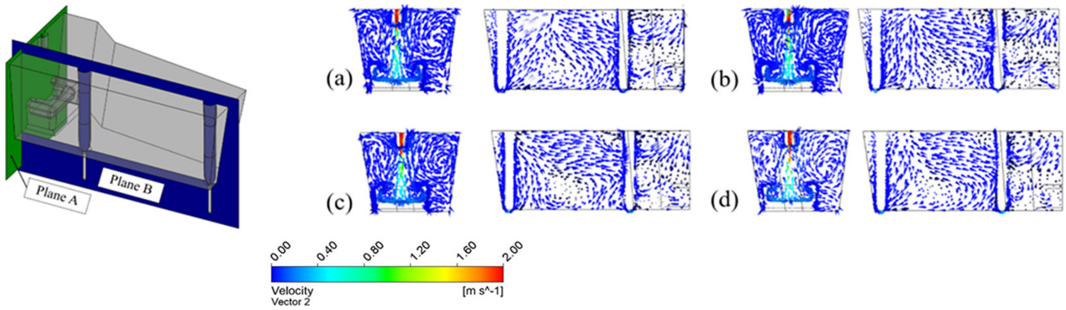

Fig. 6. The velocity flow field in the tundish with flow modifiers with different casting speeds of (a) case A; (b) case B; (c) case C and (d) case D.

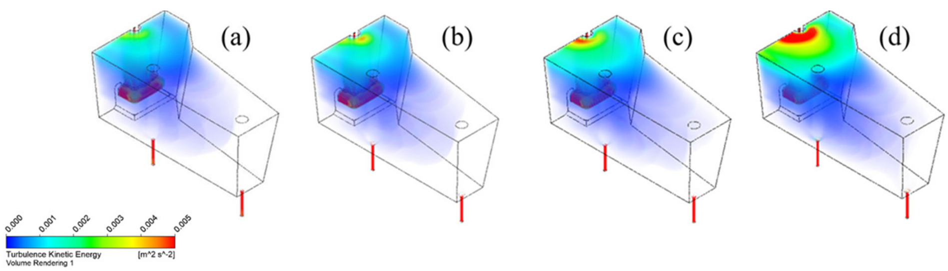

Fig. 7. Turbulence kinetic energy of different casting speeds at (a) case A; (b) case B; (c) case C and (d) case D.

2.4. Experimental setup

The simulation results were validated with the experimental results. The same parameters of simulation setup were applied in the experimental setup. The tracer including water, red dyed color and NaCI was mixed in the each of casting speed. The tracer was injected on the water by operating solenoid valve as shown Fig. 5 (a) The residence time of injected tracer starting from the inlet into the outlet position is detected the probe as shown Fig. 6(b) The conductivity of tracer was recorded in the software.

3. Results and discussion

3.1. Velocity flow field

Fig. 6 illustrated velocity flow field of all cases in the 2D cross section plane A and B. The arrow heads display the direction of the velocity of the flow characteristics with the different casting speeds while the colour bar represents the velocity scale. The flow characteristics of the two counter-rotating toroidal vortices can be observed in the plane A. Fig. 6(a-c) show similar high velocity patterns as the fluid flows from inlet to the bottom of the tundish and flows upward to the top surface. Fig. 6(d) presents the highest the velocity of flow characteristics compared to the other three cases. Plane B depicts the change of the velocity movement directions of the different casting speed of all cases.

3.2. Turbulence kinetic energy

Turbulence kinetic energy is used to describe the intensity of turbulence flow in the whole volume of each tundish. Fig. 7 illustrates the turbulence kinematic energy results of all cases. The direction of turbulence flow starts from the inlet to the bottom of tundish and flows upwards to the top surface. Fig. 7(a-c) show that the turbulence kinetic energy of cases A, B and C indicate a decrease in the level of turbulence kinetic energy. On the other

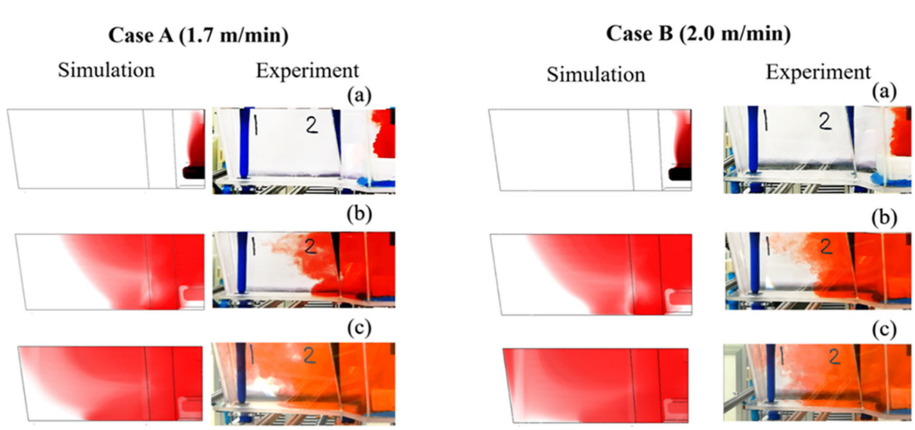

Fig. 8. The comparison of simulation results and experimental results with different casting speeds Case A (1.7 m/min); and Case B (2.0 m/min) after (a) 1; (b) 20 and (c) 50 s.

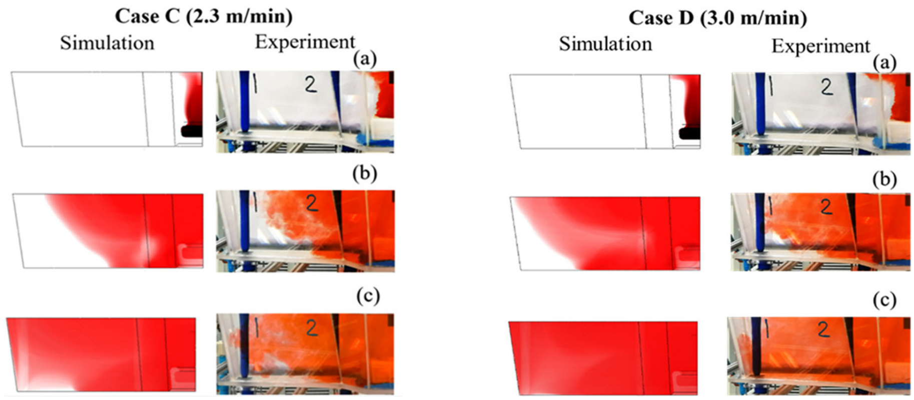

Fig. 9. The comparison of simulation results and experimental results with different casting speeds Case C (2.3 m/min); and Case D (3.0 m/min) after (a) 1; (b) 20; and (c) 50 s.

hand, case D presents that there is the highest dissipation of the turbulence kinetic energy at casting speed of 3.0 m/min, which enhances higher probability of slag eye inclusions inside the tundish compared to the other cases.

3.3. Tracer mass fraction

Figs. 8 and 9 show the comparison between the simulation results and experimental results with different casting speeds after 1, 20, and 50 s. In this research, the tracer mass fraction simulation is used to investigate the flow characteristics of liquid flow inside the tundish. The simulation results are in agreement with the physical water model.

Initially, the incoming tracer of both results of all casting speeds are similar at 1 s as shown in Fig. 9(a). Case D shows that at 20 and 50 s, the tracer of casting speed of 3.0 m/min reached the mid-outlet and the far-outlet more quickly which represents the short circuit phenomena compared to the other casting speeds. Hence, case D has higher chance to increase the inclusion inside the tundish than the other cases.

3.4. RTD analysis

RTD analysis was performed in this research to investigate the flow characteristics inside the water tundish model. The measurement of RTD has been carried out by tracer injection. The results from the water tundish model were used to validate the simulation results to apply further result analysis for the real tundish. Fig. 10 shows the correlation between the dimensionless mass fractions and times at different casting speeds from mid and far-outlets of tundish with square turbostop. Fig. 10(a) – (b) show the experimental results obtained from the physical water model while Fig. 10(c) – (d) illustrate the simulation results. The results of both simulation and experiment show good agreement with minor differences.

The colour lines represent different casting speeds of all cases. Fig. 11(a) - (b) illustrate that both experimental and simulation results present the critical point at mid-outlets. The minimum residence time, (t_{min}) which is a start point of RTD curves was used to detect the initial time that obtained from the first response of tracer concentration at the outlet position. In case D, the peak of RTD

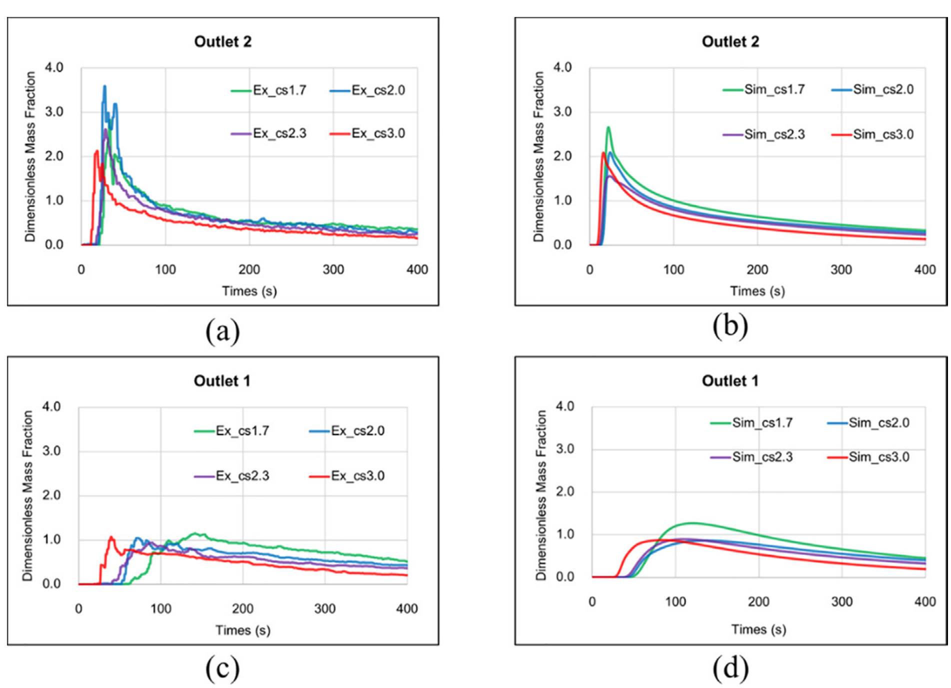

Fig. 10. RTD curves obtained from experimental results at (a) mid-outlet; (c) far-outlet; RTD curves obtained from the simulation results at (b) mid-outlet; (d) far-outlet.

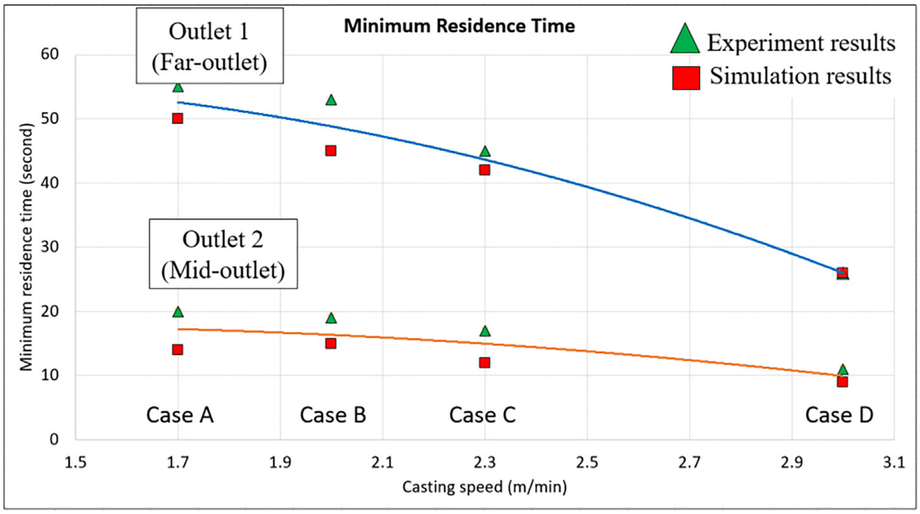

Fig. 11. . The minimum residence time of tracer in all cases between experiment and simulation results.

curve is very close to the minimum residence time point, which might have a higher chance of short circuit flow and potential inclusion inside the tundish, compared to the other case

In addition, it can be clearly seen that far-outlet-1 presents longer RTD curves, compared to that of the mid-outlet as illustrated in Fig. 11(c) - (d). The results indicate that the far-outlet could promote the inclusion removal and prevent the short circuit flow which results in the improvement of the flow characteristics inside the tundish.

In this research, the minimum residence time of RTD was studied under four different casting speed conditions which are regulated by changing flow rates at inlet and outlet. The low value of minimum residence time represent the possibility of short circuit flow and potential inclusion contamination in the tundish outlet. The minimum residence time (t_{min}) of concentration tracer recorded is shown in Fig. 11. The rectangle and square points represent the experiment and simulation results respectively. As can be observed from the trend of outlet 1, case A could prolong the minimum residence time of the tracer injection greater than other cases. It can be seen that case A can enhance inclusion removal more efficiently. On the other hand, case D has higher chance of short circuit flow and inclusion inside the tundish. Furthermore, all cases of outlet 2 present the critical zone owing to the short minimum residence time of tracer.

4. Conclusion

The physical water model and the CFD simulation were used for the study of RTD curves and flow characteristics in the tundish under four different casting speed conditions which are regulated by changing flow rates at inlet and outlet. The validation of both experimental and simulation results are in good agreement. The results show that the start point and the peak of RTD curves of mid-outlets are faster than those of far-outlets. The analysis of minimum residence time (t_{min}) was performed to predict the effect of inclusion contamination in the tundish. Case D which has highest flow rate and casting speed presents the lowest value of minimum residence times. This result shows the possibility of short circuit flow and potential inclusion contamination in the tundish outlets. The difference between minimum residence time of the far-outlet and mid-outlet is approximately 10%. In case of mid-outlet, the increase of casting speed by 1 m/min could reduce the minimum residence time for 30% approximately. Both experimental and simulation results show that mid-outlet with highest casting speed has the lowest of minimum residence times which is the critical point and leads to the chance of potential inclusion contamination and low cleanliness steel.

CRediT authorship contribution statement

Kridsanapong Boonpen: Conceptualization, Methodology, Software, Validation, Investigation, Visualization, Writing - original draft, Writing - review & editing. **Pruet Kowitwarangkul:** Supervision, Project administration, Conceptualization, Formal analysis, Investigation, Visualization, Writing - original draft, Writing - review & editing, Funding acquisition. **Patiparn Ninpetch:** Investigation, Writing - original draft, Writing - review & editing. **Nadnapang Phophichit:** Investigation, Writing - original draft, Writing - review & editing. **Piyapat Chuchuay:** Validation, Investigation. **Thotsaphon Threrujirapapong:** Supervision, Writing - original draft, Writing - review & editing. **Somboon Otarawanna:** Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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