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# Study on Parameter Optimization of Diversion Wall in an Eight-Strand Tundish during Continuous Casting of Billet with High Casting Speed

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**Abstract:** With the increasing demand for high-efficient continuous casting, parameter optimization during high-speed continuous casting is critical. To clarify the changes in flow characteristics in a multistrand tundish and the optimization principles for the diversion wall, a numerical investigation of an eight-strand tundish during continuous casting of billet was carried out in this paper. The simulation results were validated with the physical results of a 1:3 water model experiment. The results show that, for a tundish with the same flow control device, the average residence time and the maximum residence time difference of liquid steel in different strands are significantly reduced with higher casting speed. At different casting speeds, the effect of the hole diameter and deflection angle of diversion wall on the average residence time and the dead region proportion is very minor, while that on the maximum residence time difference of liquid steel in different strands is significant. For a given tundish, to improve the flow uniformity among multiple strands, parameter optimization of diversion wall should be optimized when the casting speed increases. When the casting speed is 4.4 m/min, the hole diameter of the diversion wall is 80 mm, and the deflection angle of the diversion wall is 74°, the flow field parameters of liquid steel in the eight-strand tundish are good, especially flow uniformity among multiple strands.

**Keywords:** high-speed continuous casting; average residence time; flow uniformity among multiple strands; parameter optimization of diversion wall



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## 1. Introduction

The core of the new generation of high-efficiency continuous casting technology is higher casting speed [1]. The definition of high casting speed varies according to the steel grade and strand section, and the casting speeds of round billets and slabs are lower than that of billets and thin slabs. At present, in most Chinese steel plants, the actual working casting speed of slabs, round billets, billets, and thin slabs can reach 1.8 m/min, 3.0 m/min, 4 m/min, and 5 m/min [2–5]. It is reported that the maximum experimental casting speed of billets in China is 5.7 m/min, which is produced by Yangchun Steel Company (Yangchun, China); usually, the actual working casting speeds are in the range of 4.2–4.4 m/min [6].

A series of quality problems may occur with increasing casting speed, such as surface crack, breakout, inclusion defects, midway crack, and centerline segregation. Due to the large impact depth of the molten steel stream in the mold during high-speed continuous casting, it is difficult for the inclusions to float up, which easily leads to inclusion defects. As steel cleanliness plays a significant role in steel quality, the removal of inclusions in the tundish has become the focus of steelmakers [7–9]. The core of tundish metallurgy is to control the flow field of molten steel and the removal of inclusions [10,11].

Although metallurgical workers [12–19] have performed much research on the optimization measures of the molten steel flow field in a multistrand tundish under a given casting speed, the changing law of the flow field of molten steel under high casting speeds is still unclear. Fei [20] found that increasing the far-strand's casting speed can significantly reduce the dead region proportion and flow difference among multiple strands in a five-strand tundish. Boonpen [21] used the response time (the starting point of the residence time distribution (RTD) curve) as an evaluation index of the probability of short-circuit flow and inclusions and pointed out that an increase in casting speed by 1 m/min could reduce the minimum residence time by approximately 30% in the case of a mid-outlet, which might have a greater probability of inclusion aggregation. These results are very important to clarify the influence of the casting speed on the flow field in the multistrand tundish. However, the operation of increasing the casting speed of a single flow is not convenient in actual production, and optimization measures of the flow control device in the multistrand tundish during high-speed continuous casting are also unclear.

At present, the casting speeds of Chinese steel mills have been greatly improved. Does the flow control device in the tundish need to be reoptimized under high casting speeds? How can the flow control device be optimized in a tundish? To solve the above problems, a 1:3 water model of tundish experiments and numerical simulation calculations of an eight-strand tundish during the continuous casting of billet were carried out in this paper. Then, the effect of casting speed and diversion wall parameters on the flow field in a tundish can be clearly clarified, which can provide a theoretical and technological basis for parameter optimization of the diversion wall during high-speed casting.

## 2. Model Description

### 2.1. Physical Modeling

To achieve hydrodynamic similarity of the liquid steel in a tundish, which is dominated by inertia, gravity, and viscous forces, the Reynolds and Froude numbers (Re and $Fr$) should be equal. Since the liquid in a tundish is always under a turbulent flow condition, and the flow is in the same self-modeling area, then the similarity principle does not require that the Reynolds number be equal. Therefore, in the case of geometric similarity, if the Froude numbers of water in the water model and liquid steel in the tundish are equal, as shown in Equation (1), then similar dynamics of the model and prototype can be ensured.

$$\frac{(Fr)_m}{(Fr)_r} = 1 \tag{1}$$

Here, subscript $m$ is model; subscript $r$ is prototype.

Based on the process parameters of an eight-strand tundish during the continuous casting of billet, a 1/3 water model of tundish was designed, and the corresponding dimensions of the prototype and the model are shown in Table 1. According to the Froude similarity criteria, the rates of volume flow and time between the model and the prototype are shown in formulas (2) and (3), and the volume flow of the water model under different casting speeds of billet with a 160 × 160 $mm^2$ section could be obtained.

$$\frac{Q_m}{Q_r} = (K)^{5/2} = (1/3)^{2.5} \tag{2}$$

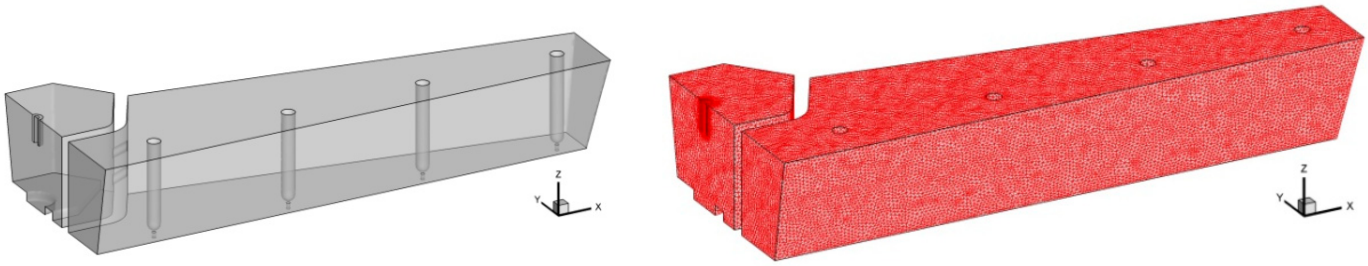
$$\frac{t_m}{t_r} = (K)^{1/2} = (1/3)^{1/2} \tag{3}$$

**Table 1.** Corresponding dimensions of tundish prototype and model ($K$ = 1/3).

| Parameters | Prototype | Model |
|---|---|---|
| Distance between two outlets/mm | 1300.00 | 433.33 |
| Depth of liquid/mm | 850.00 | 283.33 |
| Ladle shroud inner/outer diameter/mm | 60/122.00 | 20/40.67 |
| Depth of ladle shroud penetration/mm | 250.00 | 83.33 |
| Inner diameter of tundish nozzle outlet/mm | 35.00 | 11.67 |
| Stopper diameter/mm | 124.00 | 41.3 |

## 2.2. Mathematical Modeling

Based on the process parameters in Table 1, a three-dimensional tundish model of the prototype was designed. The half-section of the eight-strand tundish was simulated in the commercial software ANSYS Fluent v19.2. The model was divided into many unstructured meshes, and the inlet, outlet, and diversion holes were densified. The corresponding three-dimensional geometric model and mesh model of the tundish are shown in Figure 1.



(**a**) (**b**)

**Figure 1.** Three-dimensional model of the tundish: (**a**) geometric model; (**b**) mesh model.

The simulation was performed under the following assumptions [22]: (1) the molten steel in the tundish is an incompressible Newtonian fluid, and the physical parameters are shown in Table 2 [23]; (2) its flow state can be regarded as 3-D single-phase steady-state turbulent flow; (3) the slag layer and air above the molten steel are not considered; (4) the heat transfer of molten steel in the tundish and the influence of thermal buoyancy on the flow of molten steel are not considered; (5) the flow of the tracer with the same properties as the liquid steel is an unsteady mass transfer process.

**Table 2.** Physical parameters of liquid steel.

| Density, $kg \cdot m^{-3}$ | Dynamic Viscosity, $\mu/N \cdot s \cdot m^{-2}$ | Kinematic Viscosity, $\nu/m^{-2} \cdot s^{-1}$ | Surface Tension, $\sigma/N \cdot m^{-1}$ |
|---|---|---|---|
| 7020 | 0.0067 | $0.913 \times 10^{-6}$ | 1.6 |

The turbulent flow of molten steel in the tundish satisfies the continuity equation, momentum equation, and turbulent control equation, which can be found in reference [23]. In this research, the k-ε model was applied to predict the turbulence flow pattern in the tundish. The flow characteristics of turbulent flow phenomena were simulated by the realizable k-ε model and the SIMPLEC algorithm. The tracer with the same properties as the liquid steel was injected for 1 s into an eight-strand tundish under steady state and transient conditions, and it was used to observe the flow characteristics in the tundish.

## 2.3. Research Schemes

The control devices of the fluid field in the eight-strand tundish are a diversion wall and a turbulence inhibitor. The inclination angles of the upper hole and lower hole in the diversion wall are 25° and 30°, respectively, the hole diameters of the diversion wall (hereinafter referred to as hole diameter) were equal, and the deflection angle of the diversion wall (hereinafter referred to as deflection angle) is the angle between the centerline of the diversion hole and the centerline of the tundish, as shown in Figure 2.

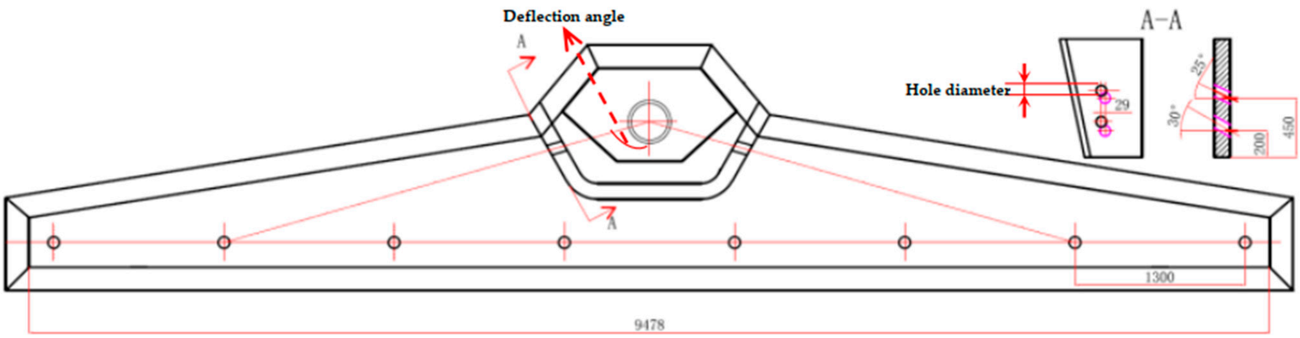



**Figure 2.** Schematic diagram of the eight-strand tundish.

In the current study, three cases were investigated, and are shown in Table 3, in which the model verification experiment (Case A), the influence of the hole diameter on the tundish flow field under different casting speeds (Case B), and the influence of the deflection angle on the tundish under different casting speeds (Case C) are shown. Four deflection angles (71°, 74°, 77°, and 79°) were chosen in Case C, as shown in Figure 3. The calculation method of the RTD curve obtained by the experiment and calculation is referred to in reference [24].

**Table 3.** Scheme of the effect of the diversion wall parameters and the casting speed on the flow field in the tundish.

| Scheme | Casting Speed, m/min | Hole Diameter, mm | Deflection Angle,° |
|---|---|---|---|
| Case A | 2.8, 3.2, 3.6, 4, 4.4 | 80 | 74 |
| Case B | 2.8, 3.6, 4.4 | 65, 80, 95, 110 | 74 |
| Case C | 2.8, 3.6, 4.4 | 80 | 71, 74, 77, 79 |

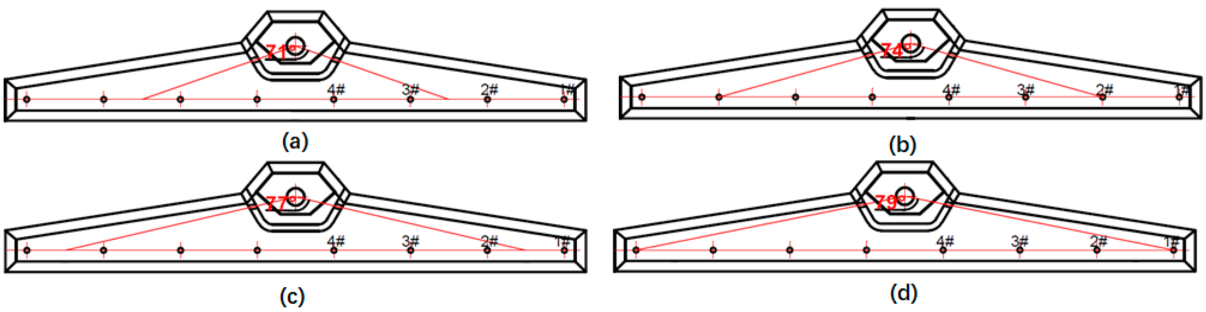



**Figure 3.** Schematic diagram of four diversion walls with different deflection angles: (**a**) 71°; (**b**) 74°; (**c**) 74°; (**d**) 79°.

## 3. Model Verification

### *3.1. Verification of Mesh Irrelevance*

Computational meshes of 1.7 million, 1.9 million, and 3.4 million elements were used in the Computational Fluid Dynamics (CFD) simulation to verify the irrelevance of mesh size. The process parameters for the validation calculations were as follows: casting speed of 4.4 m/min, hole diameter of 80 mm, and deflection angle of 74°. The RTD curves of outlet 1# in the tundish for different mesh numbers are shown in Figure 4. It can be seen that the outlet concentration is independent of mesh size. Taking into account the performance of the computer and the efficiency of the calculation, 1.9 million elements were used in the numerical simulation.

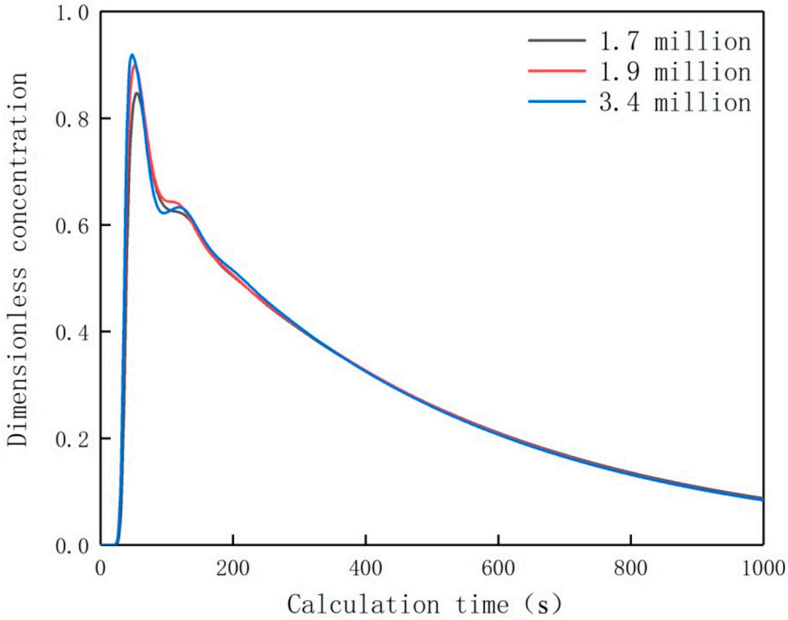
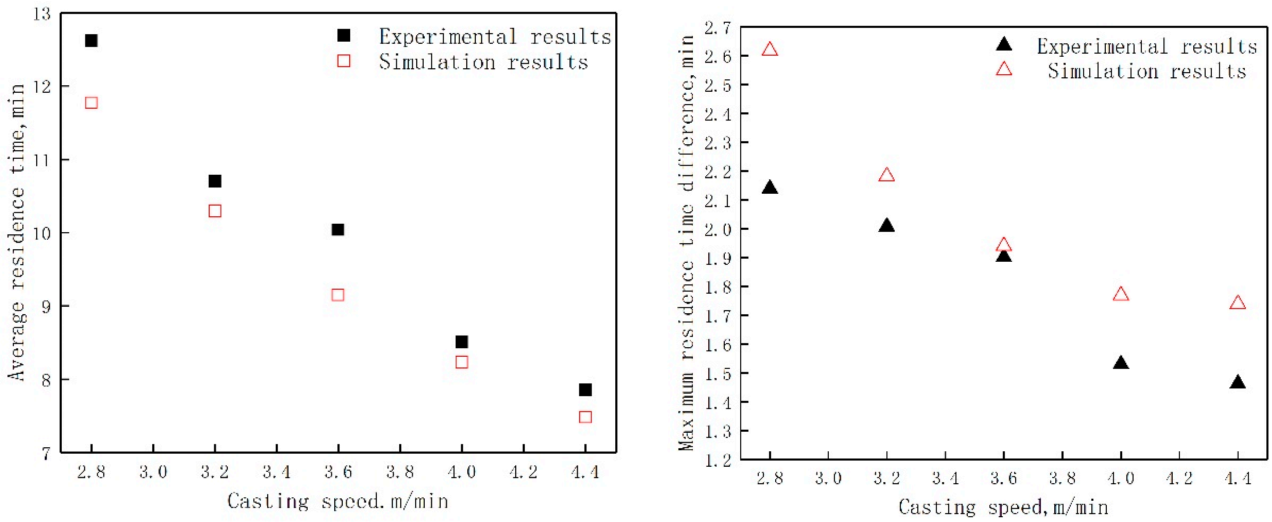



**Figure 4.** Tracer concentration at outlet 1# at different grid numbers.

### *3.2. Validation of Numerical Modeling Results*

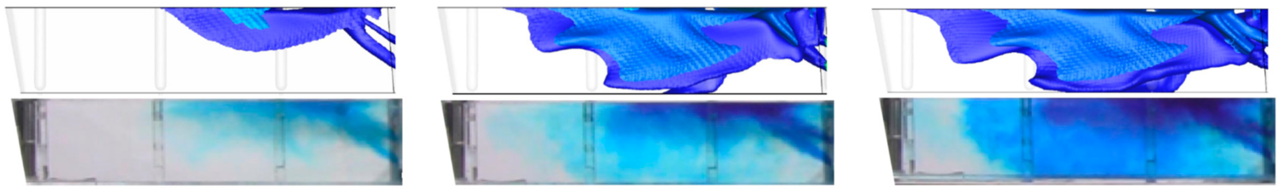
Figure 5 shows the comparison of the characteristic flow parameters between the simulation results and experimental results with different casting speeds for a given tundish with a hole diameter of 80 mm and a deflection angle of 74°. It is shown that both the average residence time and the maximum residence time difference of liquid steel in different strands (hereinafter referred to as maximum residence time difference) calculated by the numerical simulation are in better agreement with the water model results. As shown in Figure 5a, the average residence time decreased significantly with higher casting speed because the liquid steel can reach the outlet in a shorter period of time. Due to the low average residence time, there is not enough time to float the inclusions during high-speed continuous casting. The maximum residence time difference also decreased significantly with higher casting speed, as shown in Figure 5b, which means that the flow uniformity among multiple strands was improved during high-speed continuous casting.

Figure 6 shows the comparison of the flow field between the simulation results and experimental results at a casting speed of 4.4 m/min after adding a tracer at different times for a given tundish with a hole diameter of 80 mm and a deflection angle of 74°. It was observed that the liquid that exited through the upper hole in the diversion wall formed a near-surface laminar flow. The liquid with the tracer moved to approximately one-half of the entire area at 10 s, moved from top to bottom towards outlets 1–3# at 20 s, and gradually flowed towards outlets 1–4# at 30 s. From the color shades of liquid in Figure 5, the flow uniformity among multiple strands is observed directly. Compared with the flow field between the simulation results, it can be seen that the overall flow characteristics of both the simulation and experiment showed good agreement; thus, the numerical simulation approach taken in this paper is reliable.




(**a**) (**b**)

**Figure 5.** Comparison of characteristic parameters of flow between the simulation results and experimental results with different casting speeds: (**a**) average residence time; (**b**) maximum residence time difference.



(**a**) (**b**) (**c**)

**Figure 6.** Comparison of experimental results of the flow field at a casting speed of 4.4 m/min after adding the tracer at: (**a**) 10 s; (**b**) 20 s; (**c**) 30 s.

## 4. Results and Analysis

### *4.1. Influence of Diversion Wall Parameters on Average Residence Time and Dead Region Proportion of Liquid Steel under Different Casting Speeds*

Figure 7 shows the effect of the hole diameter on flow field parameters in tundish with a deflection angle of 74° at different casting speeds. When the casting speed increased from 2.8 m/min to 4.4 m/min, liquid steel in the tundish with a hole diameter of 65 mm had smallest average residence time and largest dead region proportion, while that in the tundish with a hole diameter of 80 mm had the largest average residence time (7.49 min) and smallest dead region proportion (10.5%). This is because the flow velocity and flow rate of liquid steel, which together affect average residence time and dead region proportion, would change with the diversion hole. However, the influence of hole diameter on the average residence time and dead region proportion of liquid steel at a given casting speed was very small.

Figure 8 shows the effect of the deflection angle on the flow field parameters in the tundish with a hole diameter of 80 mm at different casting speeds. When the casting speed increased from 2.8 m/min to 4.4 m/min, liquid steel in the tundish with deflection angles of 71° and 77° had a relatively large average residence time and a relatively small dead region proportion, while that in the tundish with the deflection angles of 74° and 79° had a relatively small average residence time and a relatively large dead region proportion. However, the influence of deflection angles on average residence time and dead region proportion at a given casting speed is very small.

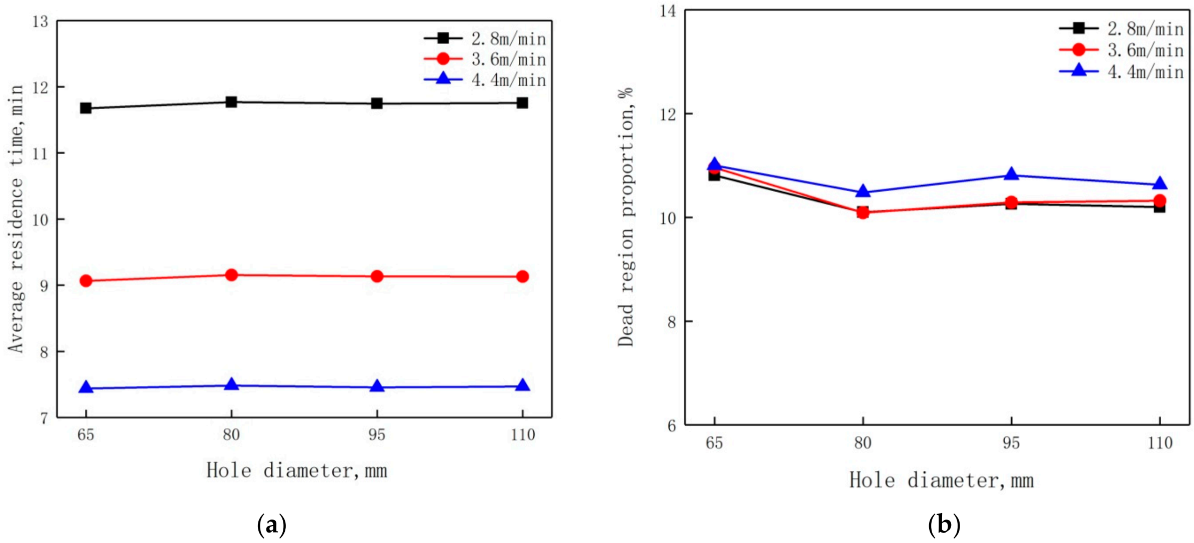



**Figure 7.** Effect of hole diameter on flow field parameters in the tundish at different casting speeds: (**a**) average residence time; (**b**) dead region proportion.

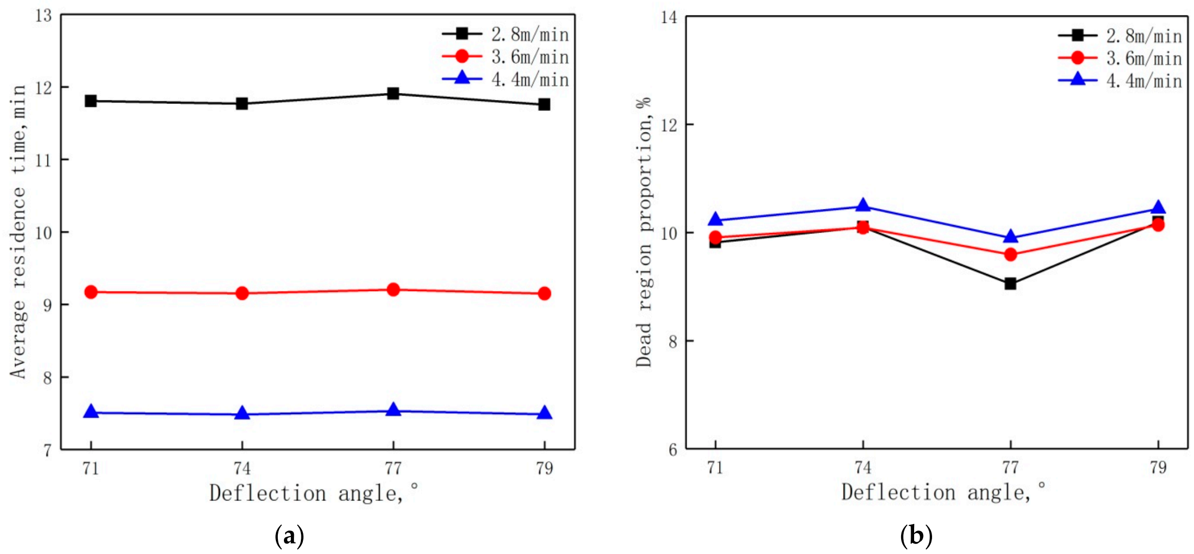
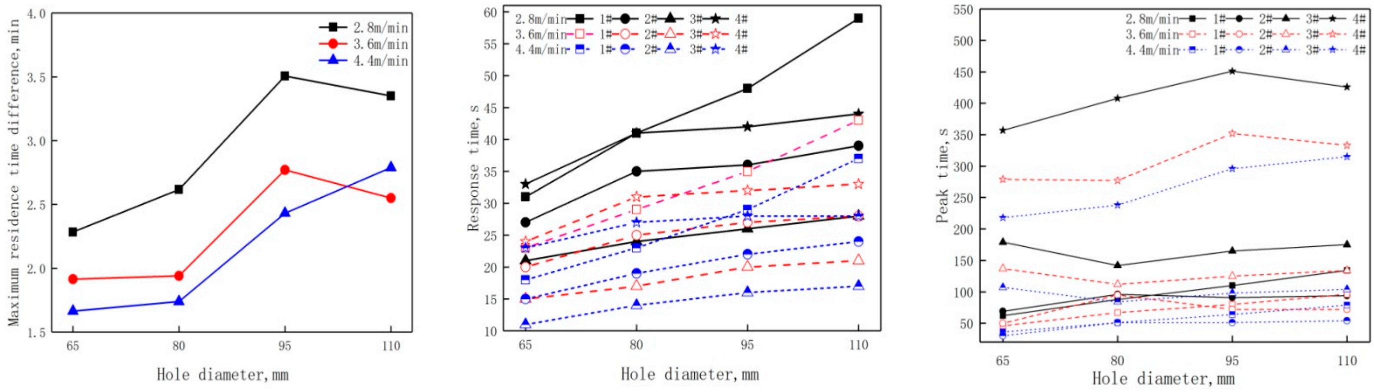



**Figure 8.** Effect of the deflection angle on flow field parameters in the tundish at different casting speeds: (**a**) average residence time; (**b**) dead region proportion.

### *4.2. Influence of Diversion Wall Parameters on Maximum Residence Time Difference under Different Casting Speeds*

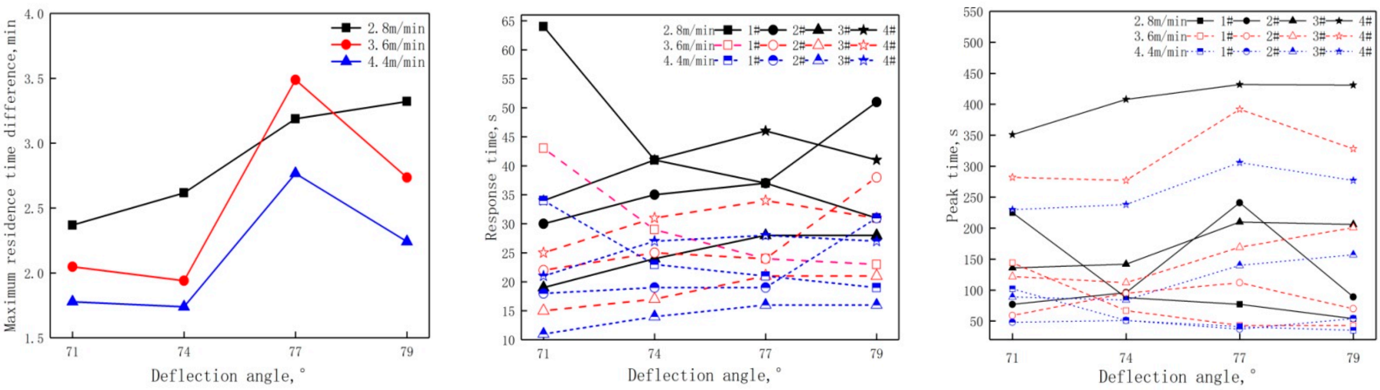
Figure 9 shows the effect of the hole diameter on the flow field parameters in the tundish with a deflection angle of 74° at different casting speeds. As shown in Figure 9a, with the increase of hole diameter, maximum residence time difference increased and then decreased when the casting speed was 2.8 and 3.6 m/min, while that increased when the casting speed was 4.4 m/min. The maximum residence time difference in the tundish with hole diameters of 65 mm and 80 mm was relatively small, 1.66 min and 1.74 min when the casting speed was 4.4 m/min. Figure 9b illustrates that the response time of each outlet increased with a larger hole diameter. When the casting speed increased from 2.8 m/min to 4.4 m/min, the response times of outlets 2# and 3# in the tundish with a hole diameter of 65 mm decreased from 27 s and 21 s to 15 s and 11 s, respectively, which might have a higher chance of short circuit flow and potential inclusion inside the tundish. Figure 9c shows that with increasing casting speed, the peak time of outlet 4# in the tundish with a hole diameter of 80 mm had a maximum reduction; thus, the difference between each strand decreases.




(**a**) (**b**) (**c**)

**Figure 9.** Effect of hole diameter on flow field parameters in the tundish at different casting speeds: (**a**) maximum residence time difference; (**b**) response time; (**c**) peak time.

Figure 10 shows the effect of the deflection angle on the flow field parameters in the tundish with a hole diameter of 80 mm at different casting speeds. As shown in Figure 10a, with the increase of deflection angle, maximum residence time difference increased when the casting speed was 2.8 m/min, while that increased and then decreased when the casting speeds were 3.6 and 4.4 m/min. The maximum residence time difference in the tundish with deflection angles of 71° and 74° was relatively small, 1.78 min and 1.74 min when the casting speed was 4.4 m/min. Figure 10b illustrates that when the casting speed increased from 2.8 m/min to 4.4 m/min, the response times of outlets 2# and 3# in the tundish with a deflection angle of 71° decreased from 30 s and 19 s to 18 s and 11 s, respectively, which might have a higher chance of short circuit flow and potential inclusion inside the tundish. Figure 10c shows that with increasing casting speed, the peak time of outlet 4# in the tundish with a deflection angle of 74° had a maximum reduction; thus, the difference between each strand decreased.



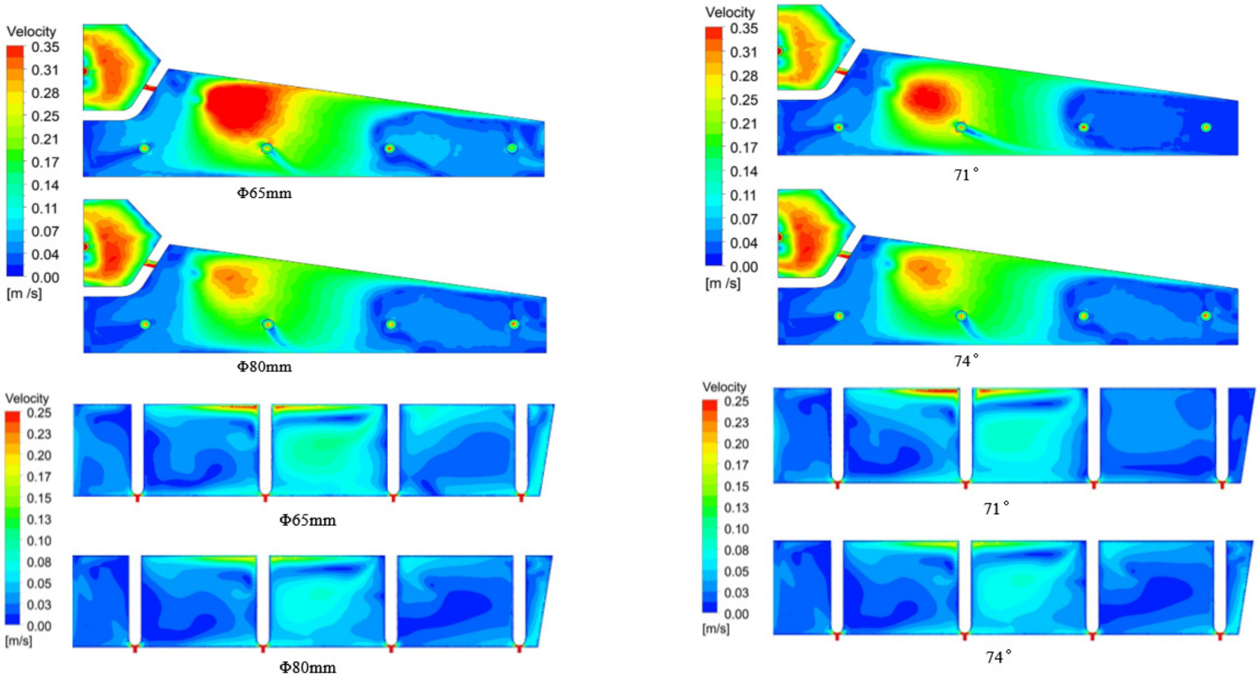

(**a**) (**b**) (**c**)

**Figure 10.** Effect of deflection angle on flow field parameters in the tundish at different casting speeds: (**a**) maximum residence time difference; (**b**) response time; (**c**) peak time.

*4.3. Parameter Optimization of Diversion Wall during High-Speed Continuous Casting*

From the above mentioned, the average residence time in the multistrand tundish in this study decreased significantly with higher casting speed, which might lead to inclusion defects. Therefore, during high-speed continuous casting, some measures to remove inclusions, such as increasing the tundish volume, should be taken. Moreover, the consistency of the quality of different strand is also a key issue during high-speed continuous casting. Due to the lower maximum residence time difference at high casting speeds, uniformity of flow and temperature among multiple strands is improved, which is beneficial for the quality uniformity and stability of strands. Since the maximum residence time difference changes with the diversion wall parameters, the design and optimization of diversion walls should be given more attention in high-speed continuous casting. In order to optimize the diversion wall parameters during high-speed continuous casting, 4.4 m/min was selected to study best hole diameter and best deflection angle.

As shown in Figures 9a and 10a, at a casting speed of 4.4 m/min, the maximum residence time difference was relatively small when the hole diameters were 65 and 80 mm and the deflection angles of the diversion wall were 71° and 74°. In order to confirm the best hole diameter and deflection angle of the given tundish in the study, the effect of the above diversion wall parameters on flow velocity field in the tundish at a casting speed of 4.4 m/min was studied, as shown in Figure 11.




(**a**) (**b**)

**Figure 11.** Velocity flow field in the tundish at a casting speed of 4.4 m/min: (**a**) with different hole diameters and a deflection angle of 74°; (**b**) with different deflection angles and a hole diameter of 80 mm.

From Figure 11a, it is observed that the flow velocity of liquid steel that exited through the diversion holes was relatively lower in the tundish with a larger hole diameter. However, the liquid level in the tundish with a diversion hole of 65 mm was not stable, and the surface velocity near stopper 3 was very high, which is detrimental to the purity of the liquid steel. From Figure 11b, it is observed that the flow velocity of liquid steel near outlet 3 and stopper 3 was relatively large in the tundish with a deflection angle of 71°, which is very easy to form short-circuit flow, slag entrapment, and stopper erosion, while that near outlet 3 and stopper 1 was not large in the tundish with a deflection angle of 74°. Considering the low maximum residence time difference and flow field characteristics, the best hole diameter and deflection angle under high casting speed for the multistrand tundish in this study were 80 mm and 74°.

## 5. Conclusions

(1) For a given tundish, both the average residence time and the maximum residence time difference decrease significantly with higher casting speed. The influence of diversion wall parameters on the average residence time and dead region proportion under different casting speeds is very small, while that on the maximum residence time difference is large.

(2) Under a high casting speed, the maximum residence time difference in the tundish increases with a larger hole diameter, while that decreases and then increases with a larger deflection angle. For the high-speed continuous casting, flow uniformity in a multistrand tundish can be improved by optimizing the deflection angle and hole diameter.

(3) When the casting speed is 4.4 m/min, the hole diameter is 80 mm, and the deflection angle is 74° for the eight-strand tundish; the average residence time is 7.49 min, the dead region proportion is 10.5%, the maximum residence time difference is 1.74 min, and the flow uniformity among multiple strands and the stable liquid surface is good.

**Author Contributions:** Y.L., P.L. and C.C. conceived and designed the study; Z.L. and W.W. conducted the experiment; Z.L. analyzed the experimental data and wrote the manuscript with the advice of Y.L., P.L., C.C., W.W. All authors have read and agreed to the published version of the manuscript.

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