Effect of bottom stirring on bath mixing and transfer behavior during scrap melting in BOF steelmaking: A review

1 Introduction

Basic oxygen furnace (BOF) steelmaking utilizes the reactions occurring between oxygen and other elements (such as carbon, silicon, and phosphorus) to form slag and increases the liquid steel temperature with the oxidization heat of impure elements. According to the classification of gas blowing parts, converters can be classified into top-blown converter, bottom-blown converter, and top-bottom combined blown converter [1,2]. Currently, top-bottom combined blown converter is the most widely used in modern steelmaking plants, and it has developed in terms of safety, stability, and high productivity [3]. According to the statistics from World Steel Association, 70.8% of the world crude steel were produced by combined blown converters in 2021 [4]. Figure 1 illustrates the schematic of combined blown converter. Highly pure oxygen is blown as a supersonic jet into the furnace through oxygen lance (known as top blowing) that oxidizes carbon and other impurities in the molten bath. Meanwhile, the gas is injected through the bottom nozzles (known as bottom stirring) into the molten bath [5–9]. Nowadays, the top-bottom combined blown converters have become the most efficient method to produce high-quality steel [10–12]. As shown in Figure 2, the coupling of the top blowing and bottom stirring is beneficial to enhance the mixing in molten bath, and reduce the oxygen content of liquid steel [13–15]. In top-bottom combined blown converters, bottom stirring plays a major role in bath mixing and is affected by several parameters like amount of gas injected, number of nozzles used, and nozzle configuration [16–21]. There is a need for optimization of bottom stirring under a given set of parameters to achieve a preferable mixing in the molten bath. The present state of the art showed that continuous efforts were made in the past to improve the bath mixing through the optimization of bottom gas flowrate, nozzle number and configurations, and gas flowrate distribution mode.

With wide concern on green and low-carbon steelmaking process, the reasonable recycling and rapid melting
of scrap in steelmaking have drawn more and more attention. Converter steelmaking is one of the significant ways to consume scrap, and how to promote the rapid melting of scrap in molten bath is still a challenge. Bottom stirring has a great influence on heat and mass transfer during scrap melting process, and the previous work has indicated that the enhanced stirring induced by bottom stirring could accelerate the scrap melting in molten bath [22–25]. Therefore, the effect of bottom stirring on transfer behavior during scrap melting, optimizing the bottom stirring parameters to accelerate the scrap melting in liquid steel was one of the emphasis in this study.

In the following chapters, the authors summarize the work from previous publications about the effect of bottom stirring parameters on bath mixing and influence of bottom stirring on heat and mass transfer for scrap melting in liquid steel.

2 Research methods

Converter steelmaking is a complex process with high-temperature physicochemical reactions and multiphase flow. It is difficult to perform the actual measurements because of extreme high temperature, and observation of flow field in molten bath becomes extremely challenging [26–28]. Currently, water model and numerical simulations are extensively used to study the fluid dynamics [29–32] and mixing characteristics [33–37] in converter bath due to their economy and practicability. Furthermore, industrial experiments [38–43] are applied to verify metallurgical effect of optimal bottom stirring scheme obtained by water model and numerical simulation.

2.1 Water model

Since the dynamic viscosity of water at the room temperature is nearly equal to that of the molten steel at 1,600°C,
water is used as the working fluid in most of the water model experiments. Numerous investigators have simulated the mixing behavior of BOF vessels in water models by measuring the time required to homogenize the liquid [44–47]. Figure 3 presents the schematic of water model for the mixing in converter bath. Based on the similarity principle, the modified Froude number \( Fr' \) is usually adopted to keep the dynamic similarity between the prototype and the model, and the expression of modified Froude number is shown in equations (1) and (2).

\[
Fr'_m = Fr'_p, 
\]

\[
\frac{u^2_m}{gL_m \rho_{L_m} - \rho_{g_m}} = \frac{u^2_p}{gL_p \rho_{L_p} - \rho_{g_p}},
\]

where \( u \) is the gas velocity, m·s\(^{-1}\); \( \rho \) is the density, kg·m\(^{-3}\); \( L \) is the characteristic length, m; \( g \) is the gravity acceleration, m·s\(^{-2}\); and subscript \( m \) stands for the model, \( p \) for the prototype, \( L \) for the liquid phase, and \( g \) for the gas phase.

In water model experiments, water, compressed air, and oil (vegetable oil, engine oil, etc.) are usually used to simulate the liquid steel, bottom gas, and slag, respectively. The mixing degree of converter bath is usually evaluated by the mixing time, which is an important index to characterize the stirring intensity of molten bath under different parameters. The authors regarded that the water model was a commonly used method to qualitatively analyze the effect of different bottom stirring parameters on bath mixing, but it was difficult to precisely repeat the actual bath flow and the results may differ greatly due to different experimental conditions.

### 2.2 Numerical simulation

With the development of Computational fluid dynamics (CFD) and computer technique, numerical simulation has drawn more and more attention in characterizing the flow behavior in converter bath, such as velocity distribution, turbulent kinetic energy, and wall shear force. In order to optimize the mixing condition in converter bath, it is important to develop experimentally validated CFD models that could depict the gas–liquid flow behavior and liquid-phase mixing accurately, and clarify the dynamic characteristics of gas–liquid flow generated by different bottom stirring parameters.

In recent years, numerous CFD simulations have been conducted to study the effect of bottom gas flowrate, and nozzle number and configurations on bath flow and mixing intensity, which is depicted in Figure 4. Normally, the dynamic conditions of the converter are studied by coupling the volume of fluid (VOF) and discrete particle models (DPM) [48–50]. VOF model is a multiphase flow model, which is generally utilized to describe the interface of different phases, and DPM is applied to clarify the motion behavior, size, and distribution of bottom bubbles. With the contours of numerical simulation, the phase distribution, magnitude, and velocity distribution, turbulent kinetic energy could be easily obtained. Meanwhile, the vectors and path lines could depict the number, direction, and distribution of circulations. The above computational results could provide a good reference for the optimization of bottom stirring parameters to achieve a preferable mixing. However, the authors considered that the establishment of
accurate and reliable mathematic models that depicted the converter bath flow was still challenging, and the industrial applicability of these mathematic models needed to be further studied.

### 2.3 Industrial experiments

Through the water model and numerical simulations, the optimal bottom stirring scheme (such as bottom gas flowrate, nozzle number, and configurations) could be obtained, which would provide a reference for industrial process. However, it is difficult to verify the technical efficiency of the optimal bottom stirring scheme. Industrial experiments are usually adopted to illustrate the metallurgical effect of improved bath mixing with the optimized bottom stirring. The control of bottom stirring intensity and slag layer thickness is crucial for BOF bottom stirring, which would directly affect the bath mixing and dynamics of molten bath in BOF steelmaking. In order to alleviate the abrasion of bottom nozzles, low-intensity bottom stirring (0.03–0.08 m³·min⁻¹·t⁻¹) is usually adopted in Chinese steel plants, which is far below that of major foreign steel plants (0.1–0.2 m³·min⁻¹·t⁻¹) [41], and the bottom nozzles tend to clog easily. In addition, the increase in the bottom slag layer thickness caused by slag splashing would also block the bottom nozzles and deteriorate the performance of bottom stirring in converter steelmaking. Therefore, in order to make full use of bottom stirring, the reasonable control of bottom stirring intensity and slag layer thickness with industrial experiments has attracted more and more attention in modern BOF steelmaking process. Some steel plants intended to enhance the converter bath mixing by simultaneously increasing the bottom stirring intensity and reducing the bottom slag layer thickness. Ultimately, technical efficiency was acquired, which is shown in Table 1. As depicted in Table 1, after the optimal control for BOF bottom stirring (the bottom stirring intensity was increased from 0.030 to 0.200 m³·min⁻¹·t⁻¹, the bottom slag layer thickness was decreased from 200 to 100 mm), the end-point carbon and oxygen equilibrium [% C]·[% O] was decreased from 0.0024 to 0.0015 for Ma steel plant.

### 3 Effect of bottom stirring parameters on dynamics of bath flow and mixing

The stirring intensity of converter bath would directly affect the reaction rate and end-point composition of liquid steel [52]. Since the stirring induced by gas injected from bottom nozzles has profound impact on steel quality, intensive work has been conducted on the mixing behavior caused by different bottom gas flowrate, nozzle number and configurations, and bottom gas distribution mode. Some of the published works regarding the bottom stirring for BOF vessels are listed in Table 2.

### Table 1: Industrial experiments with optimized bottom stirring

<table>
<thead>
<tr>
<th>Steel plant</th>
<th>Increase in bottom blowing intensity (m³·(min·t)⁻¹)</th>
<th>Reduction in bottom slag layer thickness (mm)</th>
<th>Decrease in [% C]·[% O]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benxi steel [39]</td>
<td>0.026 → 0.103</td>
<td>300 → 100</td>
<td>0.0031 → 0.0023</td>
</tr>
<tr>
<td>Shougang steel [38]</td>
<td>0.033 → 0.056</td>
<td>800 → 600</td>
<td>0.0026 → 0.0020</td>
</tr>
<tr>
<td>Ma steel [42]</td>
<td>0.030 → 0.200</td>
<td>200 → 100</td>
<td>0.0024 → 0.0015</td>
</tr>
</tbody>
</table>

![Figure 4: Flow characteristics of converter bath: (a) flow field and (b) velocity distribution.](image-url)
<table>
<thead>
<tr>
<th>No.</th>
<th>Investigators (year)</th>
<th>Multiphase system</th>
<th>Research focus</th>
<th>Methods</th>
<th>Blowing parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Singh et al. [46] (2007)</td>
<td>Gas-steel</td>
<td>Mixing time</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom nozzle configurations</td>
</tr>
<tr>
<td>2</td>
<td>Choudhary et al. [44] (2006)</td>
<td>Gas-steel</td>
<td>Mixing time and metallurgical effect</td>
<td>Cold model experiment, industrial experiment</td>
<td>Bottom nozzle configurations</td>
</tr>
<tr>
<td>3</td>
<td>Li et al. [45] (2018)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom gas flowrate</td>
</tr>
<tr>
<td>4</td>
<td>Sun et al. [47] (2022)</td>
<td>Gas-steel</td>
<td>Mixing time and velocity distribution</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>5</td>
<td>Quiyoom et al. [51] (2018)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom gas flowrate, bottom nozzle configurations</td>
</tr>
<tr>
<td>6</td>
<td>Wu et al. [53] (2015)</td>
<td>Gas-steel</td>
<td>Bath flow and metallurgical effect</td>
<td>Numerical simulation, industrial experiment</td>
<td>Bottom gas flowrate, bottom nozzle configurations</td>
</tr>
<tr>
<td>7</td>
<td>Yang et al. [19] (2014)</td>
<td>Gas-steel-slag</td>
<td>Mass transfer rate, mixing time and metallurgical effect</td>
<td>Cold model experiment, industrial experiment</td>
<td>Bottom nozzle configuration and number</td>
</tr>
<tr>
<td>8</td>
<td>Gerlach et al. [54] (1993)</td>
<td>Gas-steel-slag</td>
<td>Mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate,</td>
</tr>
<tr>
<td>9</td>
<td>Wang et al. [55] (2022)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom nozzle configuration and number</td>
</tr>
<tr>
<td>10</td>
<td>Zhou et al. [56] (2014)</td>
<td>Gas-steel</td>
<td>Mixing time, bath flow, and metallurgical effect</td>
<td>Cold model experiment, numerical simulation,</td>
<td>Bottom gas flowrate,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>industrial experiment</td>
<td>Bottom nozzle configuration and number</td>
</tr>
<tr>
<td>11</td>
<td>Stisovic et al. [57] (2002)</td>
<td>Gas-steel</td>
<td>Mixing time</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>12</td>
<td>Kawabe et al. [58] (2017)</td>
<td>Gas-steel-slag</td>
<td>Mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>13</td>
<td>Zhou et al. [59] (2016)</td>
<td>Gas-steel</td>
<td>Bath flow</td>
<td>Numerical simulation</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>14</td>
<td>Zhong et al. [61] (2006)</td>
<td>Gas-steel</td>
<td>mixing time</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>15</td>
<td>Cai et al. [60] (2023)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>16</td>
<td>Wu et al. [64] (2005)</td>
<td>Gas-steel-slag</td>
<td>Mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>17</td>
<td>Singh et al. [17] (2009)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>18</td>
<td>Yao et al. [37] (2020)</td>
<td>Gas-steel</td>
<td>Mixing time, bath flow, and metallurgical effect</td>
<td>Cold model experiment, numerical simulation,</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>industrial experiment</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>20</td>
<td>González-Rivera et al. [66] (2022)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate</td>
</tr>
<tr>
<td>21</td>
<td>Chu et al. [34] (2016)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and bath flow</td>
<td>Numerical simulation</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>22</td>
<td>Ajmani et al. [33] (2005)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>23</td>
<td>Olivares et al. [67] (2002)</td>
<td>Gas-steel</td>
<td>Mixing time</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom gas flowrate and nozzle configurations</td>
</tr>
<tr>
<td>24</td>
<td>Quiyoom et al. [30] (2017)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment, numerical simulation</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>25</td>
<td>Liu et al. [68] (2017)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and mass transfer rate</td>
<td>Cold model experiment</td>
<td>Bottom gas distribution mode</td>
</tr>
<tr>
<td>26</td>
<td>Gao et al. [62] (2023)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment, numerical simulation</td>
<td>Nozzle configurations</td>
</tr>
<tr>
<td>27</td>
<td>Gao et al. [63] (2024)</td>
<td>Gas-steel</td>
<td>Mixing time and bath flow</td>
<td>Numerical simulation</td>
<td>Nozzle configurations</td>
</tr>
<tr>
<td>28</td>
<td>Liu et al. [73] (2016)</td>
<td>Gas-steel-slag</td>
<td>Mixing time and bath flow</td>
<td>Cold model experiment</td>
<td>Bottom gas flowrate and nozzle number</td>
</tr>
</tbody>
</table>
3.1 Bottom gas flowrate

According to previous investigations, the effect of bottom gas flowrate on bath mixing was relatively consistent. A moderate increase in bottom gas flowrate was believed to reduce the mixing time, which is shown in Figure 5. Meanwhile, the proportion of dead zone where the flow velocity was relatively low in molten bath decreased and the average velocity of liquid steel increased with the increase in bottom gas flowrate [55,57,58,64,65,67]. Some reported literature revealed that there was an obvious linear relationship between the mixing time and one-third power of gas flowrate [69–72]. However, as shown in Figure 5, in the investigations of Li et al. [45], Cai et al. [60], Zhang et al. [74], and Zhong et al. [75], the results showed that the mixing time did not decrease infinitely with the increase in the bottom gas flowrate, especially when bottom gas flowrate exceeded the critical value, the mixing performance in converter bath became worse. The reason could be attributed that when the bottom gas flowrate was excessively large, the plumes induced by gas injected from bottom nozzles would penetrate the whole liquid bath and the interaction between the plumes became intensive and detrimental, which would lead to the oscillation of molten bath and dissipation of stirring energy.

According to the above analyses, bottom gas flowrate was a significant parameter for bottom stirring. An excessive increase in bottom gas flowrate would aggravate the erosion of bottom nozzles and furnace lining. Therefore, the authors regarded that resolving the contradiction between bottom nozzle longevity and bottom gas flowrate, revealing the coupled effect of bottom gas flowrate and other parameters on dynamics of bath flow and mixing should be emphasized in future works.

3.2 Nozzle number and configurations

The stirring subzone would be formed due to the rising bubble injected from each bottom nozzle [75], and nozzle number and configurations affected the interaction between each subzone, eventually the mixing of converter bath was bound to be differ greatly. The effects of bottom gas flowrate (Q) and the nozzle number (N) on the mixing time (τ) were studied in previous works and the relationship between them was obtained, which is depicted in Eq. (3) [76].

\[
\tau = 41.8 \left( \frac{Q}{N} \right)^{-0.33},
\]

where Q is the gas flowrate, Nm³·h⁻¹, τ is the mixing time, s.

However, it was found that the optimal nozzle number and configurations were different in published works due to the diversity of converter capacity, operating parameters, and experimental conditions. For example, in regard to the effect of pitch-to-circle diameter ratio on dynamics of bath flow and mixing, the results of previous investigations are shown in Table 3. Although the optimal PCD for various converter was diverse, there was a consensus that when the bottom nozzles were arranged at 0.3D–0.6D (D is the diameter of converter bath), a preferable mixing performance could be obtained. Moreover, scholars consistently agreed that the bottom nozzles should not be blindly moved to the furnace wall in order to enhance the mixing near the converter wall, which would lead to violent collision between liquid steel and the wall, resulting in the loss of stirring energy and deterioration of mixing condition in converter bath.

Table 3: Optimal PCD in previous investigations

<table>
<thead>
<tr>
<th>No.</th>
<th>Investigators (year)</th>
<th>Optimal PCD</th>
<th>Converter capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Singh et al. [46] (2007)</td>
<td>0.5D</td>
<td>160 t</td>
</tr>
<tr>
<td>2</td>
<td>Wu et al. [53] (2015)</td>
<td>0.55D</td>
<td>210 t</td>
</tr>
<tr>
<td>3</td>
<td>Wang et al. [55] (2022)</td>
<td>0.6D</td>
<td>120 t</td>
</tr>
<tr>
<td>4</td>
<td>Zhang et al. [74] (2021)</td>
<td>0.3D</td>
<td>300 t</td>
</tr>
<tr>
<td>5</td>
<td>Zhao et al. [77] (2022)</td>
<td>0.45D</td>
<td>80 t</td>
</tr>
<tr>
<td>6</td>
<td>Liu et al. [48] (2022)</td>
<td>0.42D</td>
<td>200 t</td>
</tr>
<tr>
<td>7</td>
<td>Gao et al. [62,63] (2023, 2024)</td>
<td>0.5D</td>
<td>260 t</td>
</tr>
</tbody>
</table>
In fact, the configuration of bottom nozzles includes the PCD and angle between nozzles, and the coupling effect on dynamics of bath flow and mixing should be further studied. Considering the diversity of the PCD and angle between nozzles, the configuration of bottom nozzles reported in published literature was divided into four categories in this work: (a) equiangular and equal PCD; (b) equiangular and unequal PCD; (c) non-equiangular and equal PCD; and (d) non-equiangular and unequal PCD, which is shown in Figure 6.

Based on the classification of nozzle configurations presented in Figure 6, the optimal nozzle configurations recommended in published papers are depicted in Table 4. Zhou et al. [56] found that the asymmetric nozzle configuration was the best scheme, which could achieve the shortest mixing time in converter bath. However, the symmetric and non-equiangular arrangement was found to perform best in the work of Choudhary et al. [44]. According to Table 4, it was believed that relatively concentrated configuration for bottom nozzles was beneficial for bath mixing, which could provide a good reference for the optimization and application of bottom nozzle configuration in BOF steelmaking. Through analyzing the previous work about the effect of nozzle number on bath mixing, it was found that the optimal nozzle number was relevant to converter capacity. Generally speaking, the larger the converter, the more nozzles were required. Yang et al. [19] suggested that the optimal bottom nozzle number for 300t converter was 16 in their work. Ajmani and Chatterjee [33] and Olivares et al. [67] revealed that the mixing time decreased with the increase in the nozzle number. But other investigators concluded that excessive increase in nozzle number was harmful for converter bath flow and mixing instead. The nozzle number and configuration had significant effect on dynamics of converter bath; however, the conclusions differed greatly due to the differences in experimental conditions. From the published literature, the authors concluded that there were various studies on the influence of nozzle number and configuration, respectively, but the research about the combined effect of them was still limited. Thus, the influence degree of nozzle number and configuration, and their coupling effect on dynamics of bath flow and mixing under the same experimental conditions should be focused in future works.

### 3.3 Bottom gas distribution mode

In order to make full use of the stirring energy induced by bottom stirring, adjustment of gas distribution mode for

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
No. & Investigators (year) & Optimal configurations \\
\hline
1 & Quiyoom et al. [51] (2018) & \includegraphics[width=0.2\textwidth]{image1} \\
\hline
2 & Zhong et al. [61] (2006) & \includegraphics[width=0.2\textwidth]{image2} \\
\hline
3 & Lai et al. [35] (2008) & \includegraphics[width=0.2\textwidth]{image3} \\
\hline
4 & Choudhary and Ajmani [44] (2006) & \includegraphics[width=0.2\textwidth]{image4} \\
\hline
5 & Zhou et al. [59] (2016) & \includegraphics[width=0.2\textwidth]{image5} \\
\hline
\end{tabular}
\caption{Optimal configurations in various investigations}
\end{table}
each bottom nozzle has drawn more and more attention in recent works. In general, the bottom gas distribution mode could be divided into uniform mode and non-uniform mode, which is presented in Figure 7. As it can be seen from Figure 7, the gas flowrate of each bottom nozzle was equal and invariant for uniform mode. On the contrary, the gas flowrate of each bottom nozzle was unequal and divided into strong and weak blowing groups for the non-uniform mode, an obvious flowrate gradient existed between the bottom nozzles, which could improve the bath flow and mixing for BOF steelmaking.

The influence of bottom gas distribution mode on the stirring could be characterized by the flow field and energy distribution in converter bath. Compared with the uniform mode, many studies had revealed that the non-uniform mode could form asymmetrical and large-scale circular flow in molten bath, which is shown in Figure 8. Since the gas flowrate of right bottom nozzles was larger than that of left bottom nozzles, which led to the movement of the liquid steel from the right side to the left side and formation of large-scale circular flow in molten bath, eventually the dynamics of bath flow and mixing were improved [78].

 Quiyoom et al. [30] investigated the characteristics of the flow field in converter bath under different bottom gas distribution modes by means of numerical and physical simulation, and the results indicated that the asymmetric and large-scale circular flow was formed under the non-uniform mode, which significantly improved the bath flow and mixing for BOF steelmaking. Moreover, Singh et al. [17] investigated the dynamics of bath flow and mixing with different non-uniform schemes (w-type, v-type, linear-type, m-type), which are shown in Figure 9, and the results depicted that the mixing time of linear scheme was shortened by 30–35%, the mass transfer rate between slag and steel was increased by 30% compared with the uniform mode. Similarly, in the investigation of Chu et al. [34] and Sun et al. [47], the linear type was proved to perform best for converter bath mixing. The authors also applied the physical and numerical simulation to preliminarily explore the mixing effect and dynamic conditions of molten

![Figure 7: Schematic of the uniform and non-uniform mode. (a) Uniform mode, and (b) non-uniform mode.](image)

![Figure 8: Schematic of flow field in converter bath: (a) uniform mode; (b) non-uniform mode.](image)
bath under different bottom gas distribution modes, and the results are presented in Figures 10 and 11, respectively. Three kinds of gas flowrate distribution ratio were adopted in experiments, and the distribution ratio could be calculated using Eq. (4).

\[ Dr = \frac{Q_w}{Q_s}, \]

where \( Dr \) is the distribution ratio, \( Q_w \) is the gas flowrate of weak blowing groups, \( Nm^3\cdot h^{-1} \), and \( Q_s \) is the gas flowrate of strong blowing groups, \( Nm^3\cdot h^{-1} \).

As described in Figures 10 and 11, the non-uniform mode could obviously reduce the mixing time and optimize the bath flow. In addition, some scholars studied the coupling effect of gas flowrate gradient and exchange frequency on dynamics of converter bath. Figure 12 revealed the exchanging procedure of bottom gas flowrate, and the gas flowrate of bottom nozzles exchanged at intervals. The exchange frequency represented the exchange times of bottom gas flowrate in unit time. By means of exchanging the flowrate of bottom nozzles at an interval of time, the original flow field was broken, and a new flow field could be obtained [30,69]. However, the mechanism of its influence on bath mixing needs to be further investigated. The authors considered that the research work on the flow and mixing characteristics of molten bath caused by non-uniform mode was not deep enough, especially the stirring characteristics under coupling effect of gas flowrate gradient and exchange frequency was still unclear, it was urgent to carry out the abovementioned work in future.

Based on the above analysis, optimizing the bottom stirring parameters (such as gas flowrate, nozzle number and configuration, and gas flowrate distribution mode) is believed to improve the dynamic conditions of molten bath, which is helpful to the precise control of steel quality.

Figure 9: Non-uniform schemes: (a) linear-type; (b) v-type; (c) m-type; and (d) w-type.

Figure 10: Effect of bottom gas flowrate distribution mode on bath mixing.

Figure 11: Influence of bottom gas distribution mode on dynamics of converter bath.
and achieve the highly efficient steelmaking process. Under China’s carbon peaking and neutrality goals, the rapid melting and high-efficient utilization of scrap in BOF steelmaking would attract more and more attention in future. As is known to all, scrap melting is affected by the heat and mass transfer in molten bath, and the heat and mass transfer behavior could be improved by enhanced bath mixing through bottom stirring, which would provide a reasonable and practical solution for rapid melting of scrap in converter bath. The detailed research work about the effect of bottom stirring on scrap melting is described in Section 4.

4 Effect of bottom stirring on heat and mass transfer for scrap melting in molten bath

Nowadays, scrap has become an ecological and beneficial raw material for BOF steelmaking, and the scrap melting in molten bath is critical for highly efficient utilization of scrap. Generally speaking, the temperature of liquid bath and scrap [23,79], the carbon content of molten bath and scrap [80,81], the shape, spacing, and position of scrap would directly affect the scrap melting in molten bath [82–86]. Based on previous publications about the scrap melting in liquid steel, a simultaneous mass and heat transfer should be considered, which is presented in Figure 13. As shown in Figure 13, due to the carbon gradient between the molten iron and scrap (the carbon content of molten iron is usually higher than that of scrap charged in converter bath), the carbon in molten iron continuously migrates to the scrap surface after scrap is immersed in molten iron, which results in the formation of lower melting point carburized layer on the scrap surface. Meanwhile, the temperature gradient between molten iron and scrap promotes the heat transfer from molten iron to scrap, accelerating the heating of scrap rapidly to the melting point. Hence, scrap melting is a phase transition process affected by mass and heat transfer between molten iron and scrap [85]. Many scholars have investigated the melting behavior of scrap in the molten bath through theoretical analysis [87–90], thermal experiments [91–93], water model experiments [22,94,95], and numerical simulations [96–98]. In Sections 4.1 and 4.2, the effect of bottom stirring on heat and mass transfer for scrap melting in converter bath is summarized in detail, respectively.

4.1 Effect of bottom stirring on heat transfer

Generally, bottom stirring could obviously improve the heat transfer between hot liquid steel and cold scrap by increasing the heat transfer coefficient, which would significantly accelerate the scrap melting in converter bath. Gaye et al. [99,100] proposed a relationship between heat transfer coefficient \( h \) and bath stirring energy \( \epsilon \) through experimental investigations, which is presented in Eq. (5).

\[
h = 5,000 \cdot \epsilon^{0.2},
\]

where \( h \) is the heat transfer coefficient, W·m\(^{-2}\)·k\(^{-1}\), and \( \epsilon \) is the stirring energy, W·m\(^{-3}\).

Taniguchi et al. [95] and Shukla et al. [101] explored the influence of bottom stirring on the melting rate of ice ball by means of physical simulation, and the results showed that the heat transfer coefficient increased with the increase in bottom gas flowrate, which is depicted in Figure 14. Argyropoulos et al. [22] deduced the dimensionless heat transfer correlations under natural and forced convection by measuring the average heat flux transferred from molten steel.
to stationary and rotating spheres, and it was found that increasing the velocity of liquid steel could significantly decrease the melting time. In addition, similar to the bath stirring induced by injected bottom gas, electromagnetic stirring is also conducive to improve the dynamic conditions of molten bath and ultimately accelerate the scrap melting [102]. Many investigations have reached a consensus that the optimization of dynamic conditions in molten bath by bottom stirring is believed to enhance the heat transfer between molten iron and scrap, finally accelerating the scrap melting [25,101,103–105]. Hence, how to improve the dynamics of molten bath with bottom stirring and reveal the influencing mechanism of different parameters on heat transfer should be emphasized in future works.

4.2 Effect of bottom stirring on mass transfer

When the bath temperature is significantly below the melting point of scrap during the prophase of BOF steelmaking, the carbon transfer from hot metal to scrap surface is the key step that affects the scrap melting rate. Some studies have proposed that the melting point of scrap could be reduced by 78.5°C when 1% mass fraction of carbon is permeated into the scrap surface [106,107]. Considered that the carbon transfer from hot metal to scrap surface is greatly affected by dynamic conditions of molten bath, the rapid melting of scrap could be achieved by enhanced stirring with injected bottom gas for converter steelmaking. The carbon transfer coefficient is an important index that characterize the carbon transfer rate between hot metal and scrap, and the effect of various parameters (carbon content of scrap and liquid steel, temperature of scrap and liquid steel, and stirring conditions of molten bath) on carbon transfer coefficient have attracted more and more attention in recent studies. Gao et al. [23,108] evaluated the effect of the rotating speed of scrap on the carbon transfer coefficient by thermal experiments. As shown in Figure 15, the results indicated that the carbon transfer coefficient increased significantly with the increase in scrap rotating speed. Wei et al. [24] performed thermal experiments to study the influence of bottom gas flowrate on scrap melting, and the results showed that when the gas flowrate increased from 3 to 7 L·min⁻¹, the carbon transfer coefficient increased by 17.45%. Furthermore, the relationship between the carbon transfer coefficient ($k_m$) and bottom gas flowrate ($Q$) was obtained in work of Wright et al. [107] and Mazumdar et al. [109], which is presented in equations (6) and (7), respectively. In addition, Kim et al. [110] analyzed the relationship between the carbon transfer coefficient ($k_m$) and the velocity of liquid steel ($u$), which is shown in Eq. (8). The abovementioned results completely verified that favorable dynamic conditions of molten bath would promote the carbon transfer between molten steel and scrap, which accelerated the scrap melting ultimately.

$$k_m \propto Q^{0.21},$$  \hspace{1cm} (6)

$$k_m = 7.8 \times 10^{-3}Q^{0.19},$$  \hspace{1cm} (7)

$$k_m = \text{constant}(u)^{0.670},$$  \hspace{1cm} (8)

where $k_m$ is the carbon transfer coefficient, m·s⁻¹, $Q$ is the gas flowrate, Nm³·h⁻¹, $u$ is the fluid velocity, m·s⁻¹.

The authors also applied the numerical simulation to explore the effect of velocity of liquid steel on scrap melting, and the results are showed in Figure 16. It can be inferred from Figure 16 that the scrap melting increases rapidly with the increase in velocity of liquid steel. Based on the above analysis, the authors concluded that strengthening the stirring and optimizing the dynamic conditions of molten bath were found to be effective to improve the carbon transfer and ultimately accelerate the scrap melting. How to enhance the bath mixing and carbon transfer through bottom stirring should be further investigated in future studies.

5 Conclusion and outlook

This study presented the research progress on the effect of bottom stirring on bath mixing and transfer behavior
during scrap melting for BOF steelmaking. It can be concluded that the mixing time of converter bath can be significantly reduced by increasing the bottom gas flowrate, but there is a critical value of gas flowrate for increasing the stirring intensity. Due to the difference of converter capacity studied, the influence of bottom nozzle number and configuration on bath mixing is diverse in various investigations. However, it is certain that the bottom nozzle number and configuration affect the flow field by altering the amount, distribution, and interaction of circulations in molten bath, and ultimately change the dynamic conditions of converter bath. In recent years, the effect of bottom gas distribution mode on dynamics of converter bath flow and mixing has drawn more and more attention. Published studies have shown that the non-uniform mode could obviously optimize the dynamic conditions of molten bath compared with the traditional uniform mode. In addition, the scrap melting in converter bath is affected by simultaneous mass and heat transfer, the current research works have demonstrated that heat and mass transfer between scrap and molten steel could be improved by enhancing bath mixing with reasonable bottom stirring, eventually accelerating the scrap melting.

Under China’s carbon peaking and neutrality goals, as a kind of recyclable iron-containing resource, the rapid melting of scrap in converter bath through high-efficiency bottom stirring would attract more and more attention in future. However, there are still many challenges of high-efficiency bottom stirring for BOF steelmaking that need to be addressed. For example, the erosion of the nozzles and bottom furnace become serious with the increase in the stirring intensity. Hence, it is necessary to comprehensively adjust bottom stirring parameters to balance the enhanced bath mixing and longevity of nozzles and furnace. Physical and numerical simulations as well as industrial experiments have shown that non-uniform bottom mode has preferable stirring intensity and bath flow, which would attract more and more interest in future works. Nevertheless, the research on the flow and mixing characteristics of molten bath caused by non-uniform bottom stirring is not deep enough, especially the coupling effect of gas flowrate gradient and exchange frequency on bath mixing is still unclear, it is urgent to carry out the aforementioned work in future. With an increasing demand for highly efficient, low-cost, and green production for converter steelmaking, it is envisaged that the high-efficiency bottom stirring will witness extensive application in the coming years.

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