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Review

Research Progress on Injection Technology in Converter Steelmaking Process

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Abstract: During the converter steelmaking process, gas-slag-metal three-phase emulsification is realized by injecting gas to complete metallurgical tasks such as slagging, dephosphorization, decarburization, and heating. As green and intelligent development of the steel industry progresses, converter steelmaking injection technology is also constantly innovating. In this review, the types and applications of top blowing injection elements, bottom blowing injection elements, and injection the medium are reviewed. Three different types of combined blowing processes are compared. At the same time, the advantages and disadvantages of different bottom blowing elements and injection media are respectively discussed. Finally, based on the research and application status of converter injection technology, the development direction of converter steelmaking injection technology is discussed. Accelerating the innovation of converter steelmaking injection technology, especially the improvement and breakthrough of high efficiency, reductions the environmental burden, and long life technology, will play an important role in promoting the transformation and improvement of the steel industry.

Keywords: converter steelmaking; injection technology; bottom blowing element; injection medium; oxygen lance

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1. Introduction

In the 1850s, Bessemer invented the bottom air-blowing acid steelmaking process by which air was injected into a bottom chamber of the converter and then entered into the molten steel throughporous bricks; this technology was not able to dephosphorize steel [1,2]. In the 1870s, Thomas invented the bottom air-blowing basic steelmaking process, which could dephosphorize steel after decarburization [3,4]. In the 1860s, Siemens and Martin invented the open-hearth steelmaking process [5], which achieved dephosphorization before decarburization; decarburization was achieved through the iron ore powders. By this technology, the slag was over the molten metal, the nitrogen in the final steel was low and steel scraps could be used. In 1949, Professor Durrer successfully performed top blowing oxygen steelmaking experiments and stimulated the Linz Works and Donawitz Works in Austria to start the industrial-scale practice of oxygen steelmaking in 1952, this process is thus called the LD process [6,7]. Later, after some process modification, it became known as the BOF process.

The BOF process is the use of supersonic oxygen jets that impact the molten bath, promote gas-slag-metal three-phase emulsification to complete slagging, dephosphorization, decarbonization and heating [8–10]. The interaction between top blowing oxygen jets and the molten bath has an important influence on the mass and heat transfer, reaction rate, splashing, and slagging [11–13]. At the same time, the bottom blowing gas further strengthens the molten bath flow and promotes the transfer of reactive material and temperature. To further improve converter steelmaking efficiency, molten steel cleanliness, and product competitiveness [14–16], converter steelmaking injection technology has been continuously innovated and advanced, mainly concentrating on injection elements, injection media, and injection technology.

In this paper, the research status of converter steelmaking injection technology is reviewed from three aspects: the top blowing injection element, the bottom blowing injection element, and the injection medium. The application status of oxygen lances, such as the conventional supersonic oxygen lance, coherent jet oxygen lance, and secondary combustion oxygen lance, is critically discussed. At the same time, the applications of nozzle-type and brick-type bottom blowing elements and injection media are reviewed, and the advantages and disadvantages of different bottom blowing elements and injection media are discussed respectively. Finally, based on the research and application status of converter injection technology, the development direction of converter steelmaking injection technology is discussed.

2. Top Blowing Element Types and Applications

Oxygen lances are key pieces of equipment in the realization of supersonic oxygen jets in the converter steelmaking process. Their manufacturing methods and characteristics are shown in Table 1. With the continuous expansion of converter capacity, metallurgical workers [17,18] have perfected and improved the oxygen lance to meet the needs of efficient and stable refining by optimizing the structure of the supersonic nozzle, increasing the number of nozzle holes, changing the manufacturing method of the nozzle, strengthening nozzle area cooling, and so on.

Table 1. Oxygen lance manufacturings method and characteristics.

Production Method	Casting Method	Forging Method	Assembling Method
Advantages	The oxygen lance has long life, good performance and high production efficiency	Simple processing method and good thermal conductivity	Reasonable nozzle structure, good water-cooling effect, long life
Disadvantages	Easy to produce casting defects such as porosity and cracks	Short life of oxygen lance nozzles	High precision is required and the manufacturing process is complex

In order to reveal oxygen lance jet behavior and molten bath stirring characteristics, metallurgists have conducted a lot of studies using numerical simulation and water simulation. The reliability of numerical simulation results has been verified by water simulation experiments. Table 2 lists the methods and contents of the study of oxygen lance jet behavior

Table 2. The method and content of the study of oxygen lance jet behavior.

Research Methodology	Research Aspects	Specific Contents
Numerical simulation	Jet dynamics parameters	Study the attenuation law of kinetic parameters, such as jet velocity, dynamic pressure, and Mach number.
	Jet impact characteristics	Study the impact effect of jets on the molten bath through parameters such as impact depth and impact radius.
	Molten bath stirring effect	Analysis of the molten bath velocity distribution pattern.
	Furnace lining erosion pattern	Study of furnace lining erosion patterns by shear stress distribution and turbulent kinetic energy.
Water Simulation	Oxygen lance operating parameters	Study the effects of oxygen lance flow rate, lance height, and inlet pressure on jet behavior.
	Impact dent size	Study on the morphology of impact dents and molten bath splashes.
	Mixing effect	Study on the mixing effect of the molten bath by mixing time.

2.1. Conventional Supersonic Oxygen Lance

The structure of a traditional supersonic oxygen lance is given in Figure 1, where the red lines in the top view indicate the circles formed by the distance of the inlet and outlet centers of the nozzle from the axis of the oxygen lance, respectively. When the high-pressure oxygen passes through the constriction section of the Laval nozzle, the oxygen flow velocity increases and reaches sound velocity at the throat [19,20]. A supersonic jet will be formed at the nozzle outlet when the ratio of outlet oxygen pressure to inlet oxygen pressure is $P_{Outlet}/P_0 < 0.528$. During the forward process of the oxygen jet, the surrounding low-velocity gas is continuously suctioned, making the jet velocity decrease. Therefore, the oxygen stream can be divided into three sections: the potential core zone (each point velocity is equal to outlet velocity), the supersonic zone and the subsonic zone. The first two sections are collectively called the supersonic core zone. The length of the supersonic core zone is a key parameter when characterizing the jet characteristics of the supersonic oxygen lance.

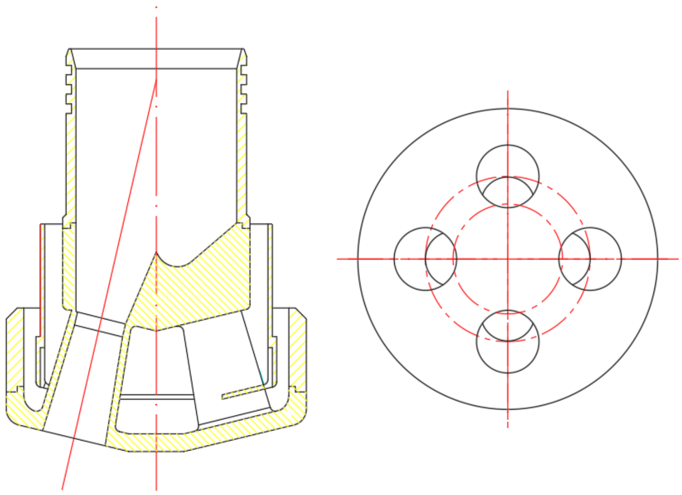

Figure 1. Schematic diagram of a traditional supersonic oxygen lance.

To further understand the performance of the supersonic oxygen lance, the gas jet characteristics and molten bath stirring characteristics were investigated using CFD models for different Mach numbers [21], operation pressures [22], ambient temperatures [23,24], nozzle hole numbers [25,26] and nozzle hole angles [27]. It was found that, when the Mach number was 2.0–2.3, the fluctuation in operation pressure had the least effect on jet velocity, and the jet velocity, impact radius, and impact depth increased with the increase in operation pressure, ambient temperature, and nozzle hole numbers. The phenomenon of jet polymerization was suppressed at high ambient temperatures, and the attenuation of jet velocity was delayed at the same time. Oxygen lances with mesoporous holes improved the three-phase emulsification of the molten bath. The phenomenon of jet polymerization increased with the increase in nozzle hole numbers. However, the results of CFD models are based on certain assumptions and do not fully reflect the actual production of the converter. Therefore, the CFD model results need to be further validated [24].

Due to limitations relating to measurement techniques and experimental equipment, water simulation studies are not entirely effective when observing and resolving the complex phenomena in the converter. Therefore, researchers established a gas-slag-metal three-phase VOF (volume of fluid) model based on the VOF interface tracking method to simulate the impact phenomena of super-sonic oxygen lance jets on the molten bath [28]. It was found that the impact dent and gas-slag-metal three-phase interface of the converter blowing process had obvious transient characteristics [29,30], and the wall shear stress near the gas-slag-metal interface was the largest [31]. As the lance height decreased, the surface velocity of molten steel increased and the surface fluctuation was strengthened; however, the velocity distribution of molten steel was more uniform at higher lance heights [32]. The above research on the multiphase flow behavior of converter molten baths reveals the change law of multiphase flow behavior, which can provide reference and guidance for the optimization of converters and the regulation of refining process parameters.

Table 3 lists the industrial tests performed by some researchers. The quality of the metallurgical effects could reflect the flow of molten steel. Oxygen lance jet behavior determines the molten bath flow state. Therefore, the jet stirring characteristics of the supersonic oxygen lance could be well verified by industry tests.

Table 3. The industrial tests carried out by some researchers.

Testers	Test Contents	Test Results
Chen et al. [33]	Optimized oxygen lance; increased nozzle hole angle and oxygen flow rate	The average smelting time and the end-point [%C]· [%O] decreased by 1.5 min and 0.0003, respectively; the dephosphorization rate increased by 4.1% and T.Fe content decreased by 1.7%.
Zhang et al. [34]	Increased nozzle hole angle and Mach number	Reduced the splashing rate, end-point [%C]· [%O], and T.Fe content by 5%, 0.0005 and 3.2%, respectively.
Lv et al. [35]	The effect of oxygen lance nozzle outlet wear angle on metallurgical effects was studied	The phosphorus content, end-point [%C]· [%O], and T.Fe content increased from 0.029%, 0.0023, and 12.92% to 0.032%, 0.0028, and 14.58%, respectively.
Liu et al. [36]	Studied the stirring ability and flow field characteristics of a conventional and nozzle-twisted oxygen lance	It showed that the 8° oxygen lance could stir molten better during the steelmaking process for the 120 t dephosphorization converter. These findings agree well with the experimental results of water experiments and numerical simulations.

2.2. Coherent Jet Oxygen Lance

To obtain greater impact depth and better molten bath stirring, the coherent jet technology developed in the EAF steelmaking process was introduced into the converter steelmaking process. Figure 2 displays a schematic diagram of coherent jet oxygen lance blowing. Adding an annular flame around the main oxygen jet provides an environment with a high temperature, high velocity, and low pressure inside the annulus. Delaying the decay of main jet velocity increases the impact force on the molten bath [37,38].

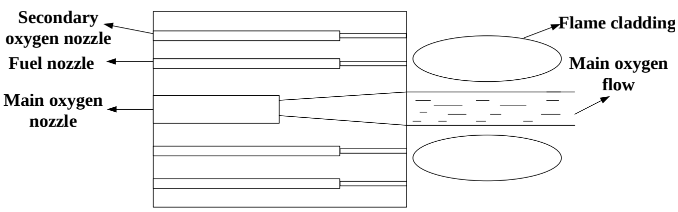

Figure 2. Schematic diagram of coherent jet oxygen lance blowing.

Metallurgists had mainly studied the effects of nozzle structure parameters [39], ambient temperature [40], type [41], pressure [42], and the temperature of accompanying gas [43] on the jet characteristics of a coherent jet oxygen lance. It was found that using a coherent jet oxygen lance could effectively suppress the radial diffusion of jet energy, prolong the high-temperature zone's length of accompanying flow, and increase the length of the jet core zone. The jet characteristics differed for different accompanying gases, with alkane concomitant gas (CH4) being better than coal gas (CO). Compared to a traditional oxygen lance, the attenuation of a coherent jet oxygen lance is slow on the center axis, its impact depth is deep, the liquid region velocity is high in the center of the molten bath, and the flow ability of the liquid steel is good in the molten bath [44].

The authors [45] studied the jet characteristics of a coherent jet oxygen lance and conducted industry tests on a 35 t converter. It was found that the converter dephosphorization rate was significantly increased. Steel charge consumption was reduced by 3.4 kg/t, and oxygen utilization and metal yield were improved.

2.3. Nozzle-Twisted Oxygen Lance

To control jet motion and suppress splashing in the molten bath, metallurgists [46–48] designed the nozzle-twisted oxygen lance and applied it to converter steelmaking. The schematic diagram of a conventional oxygen lance and nozzle-twisted oxygen lance is given in Figure 3. The nozzle-twisted oxygen lance increases the twist angle (based on a conventional oxygen lance) so that it can give rise to large a tangential force while generating axial and radial forces. The tangential force causes the molten bath to rotate horizontally, improving stirring within the molten bath [49–51].

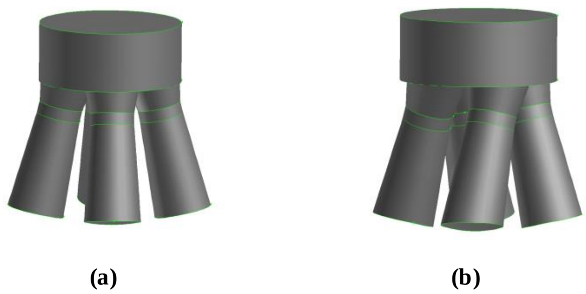

Figure 3. Schematic diagram of different oxygen lance nozzles. (**a**) conventional oxygen lance, (**b**) nozzle-twisted oxygen lance.

At present, research on nozzle-twisted oxygen lance mainly focuses on jet dynamics, molten bath stirring, splashing rate, gas-slag-metal interaction and metallurgical effect. With the increased twist angle, axial jet attenuation accelerates, the impact depth decreases, the impact area increases, and jet polymerization weakens [52]. Compared to the traditional supersonic oxygen lance, using a nozzle-twisted oxygen lance can promote steel surface flow and shorten the molten bath mixing time [53]. In addition, using a nozzle-twisted oxygen lance can reduce the splash rate and splash height [54].

Yin et al. [55] studied the slagging rate and gas-slag-metal three-phase emulsification phenomenon in the blowing process of nozzle-twisted oxygen lances. It was found that the efficiency of kinetic energy transfer at the gas-liquid interface was a key factor affecting slagging reaction; nozzle-twisted oxygen lances could accelerate the slagging reaction. Lv et al. [56] studied the jet characteristics and gas-slag-metal three-phase flow of nozzle-twisted oxygen lances. It was found that the larger the twist angle, the smaller the length of the supersonic core zone and the weaker the polymerization between the oxygen streams; slag coverage area, splash volume, and splash height were also reduced.

Due to the effective dynamic stirring effect of nozzle-twisted oxygen lances, researchers have tried to use them in converter dephosphorization, vanadium extraction, and other processes. Liu et al. [36] applied an 8° twist oxygen lance to a 120 t dephosphorization converter. The dephosphorization rate increased by 7.7% and the the T.Fe content in the slag decreased by 0.7%. The authors also applied a 10° nozzle-twisted oxygen lance to a 150 t vanadium extraction converter. The vanadium mass fraction of semi-steel was reduced by 17.8%, the converter vanadium extraction rate was increased by 5.1%, and the V2O5 yield of vanadium slag was increased by 0.93.

2.4. Secondary Combustion Oxygen Lance

A schematic diagram of a secondary combustion oxygen lance is shown in Figure 4. The secondary combustion oxygen lance enables CO to be burned twice in the furnace, allowing for reasonable use of CO energy and improving the scrap ratio, while promoting slagging [57,58]. The secondary combustion oxygen lance can be divided into single-channel oxygen lances and double-channel oxygen lances according to the position of primary and auxiliary holes [59]. The primary and auxiliary holes of single-channel oxygen lances share a common oxygen supply pipeline. The transformation process of single-channel oxygen lances is easy, with only the change of the nozzle required before it can be put into use [60]. However, the auxiliary oxygen of a single-channel oxygen lance cannot be controlled separately during the smelting process, and combustion efficiency is low. The double-channel oxygen lance adopts an independent oxygen supply pipeline, which can precisely control the flow ratio of primary and auxiliary oxygen holes and improve the combustion ratio. However, the lance structure of double-channel oxygen lances is complicated to manufacture [61].

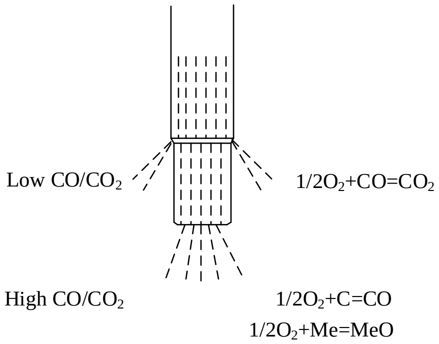

Figure 4. Schematic diagram of a secondary combustion oxygen lance.

The main indicators when evaluating the performance of a secondary combustion oxygen lance are secondary combustion rate ($CO_2/(CO+CO_2)$), secondary combustion thermal efficiency, and scrap ratio. The factors that affect the performance of secondary combustion oxygen lance are mainly primary and auxiliary oxygen hole spacing, auxiliary oxygen jet angle, and primary and auxiliary oxygen hole flow rate [62,63]. As primary and auxiliary oxygen hole spacing increases, the amount and rate of secondary combustion increases. Increasing the auxiliary oxygen jet angle aids secondary combustion in the furnace. The Sumitomo Corporation of Japan finds that combustion effect is better when the angle is 30°. When it is less than 30°, the auxiliary oxygen jet is mainly involved in the decarbonization reaction, and the combustion effect becomes worse. The primary and auxiliary oxygen hole flow rates have a direct effect on the secondary combustion amount and scrap ratio. As the proportion of auxiliary oxygen hole flow to total flow increases, the secondary combustion amount and scrap ratio increase, and when the proportion exceeds 20%, the changing trend slows down significantly.

2.5. Double-Parameter Oxygen Lance

The double-parameter oxygen lance divides the nozzle holes into two groups, and each group is designed with different nozzle hole angles, throat diameters, and Mach numbers [64,65]. A schematic diagram of a double-parameter oxygen lance is shown in Figure 5. The double-parameter oxygen lance can reduce cross-interference between the oxygen jets and splashes, and increase the impact area of the molten bath [66,67].

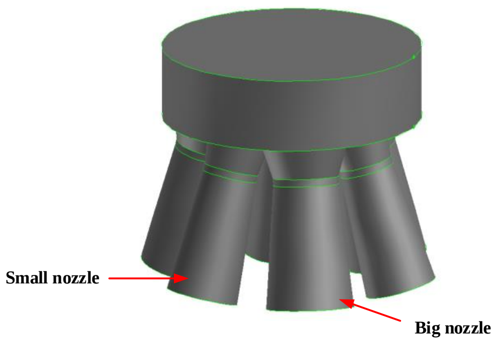

Figure 5. Schematic diagram of a double-parameter oxygen lance.

The fusion distance of double-parameter oxygen lance jets increases and then decreases with the increase in nozzle hole angle. A double-parameter oxygen lance with nozzle hole angle of 11°/11.5° has the longest fusion distance. The diagonal nozzle hole angle difference of 0.5° is conducive to increasing the fusion distance. At this time, the proportion of the weak flow zone in the molten bath is high [68]. The inclination of the small nozzle has the greatest influence on the impact diameter, and the flow rate of a large nozzle has the greatest influence on impact depth [69]. The effective impact area of the jet on the molten bath decreases gradually with the decrease in nozzle spacing. The larger the nozzle spacing, the greater the fluctuation in jet velocity. Reducing nozzle spacing can stabilize the jet velocity faster [70].

Liu et al. [71] designed a double-parameter oxygen lance, with nozzle hole inclination angles of 17° and 12° and a 60% large hole flow rate, and tested it on a 260 t converter. It was found that the average oxygen blowing time was shortened by 1 min, steel material consumption was reduced by 20.3 kg per ton of steel, and oxygen supply intensity was increased by 0.23 m3/(t·min). To improve the oxygen supply flow rate of a 300 t converter, Jiang et al. [72] designed a six-hole double-parameter oxygen lance. Through an industrial test, it was found that the average oxygen blowing time was shortened by 2.0 min, the average dephosphorization rate was 87.5%, and the average life of an oxygen lance nozzle was 190 heats.

3. Combined Blowing Process and Bottom Blowing Element Types

3.1. Combined Blowing Process

The combined blowing process is developed based on bottom blowing and top blowing. The bottom blowing gas-flow is used to strengthen molten bath stirring, so that the reaction in the converter is close to equilibrium. At the same time, the combined blowing process also retains the characteristics of the top blowing process to easily control slagging, and thus has better economic and technical indexes [73,74]. Table 4 lists the three different types of combined blowing processes.

Table 4. Three different types of combined blowing processes.

Classification	Top Blowing Oxygen, Bottom Blowing Inert Gas Process	Combined Oxygen Blowing Process	Top-Bottom Oxygen Blowing, Fuel Injection Process
Features	The bottom blowing gas is N_2, Ar and CO_2, and other weak oxidizing gases, and bottom-blowing intensity is roughly 0.3 $m^3/(t·min)$ or less. The purpose of which is to strengthen molten bath stirring.	This process refers to the simultaneous blowing of oxygen at the top and bottom, which is an intensive refining type of combined blowing process.	This technology refers to top blowing oxygen and bottom blowing or side-blowing oxygen, while bottom blowing into the fuel, which is used to increase scrap types in the combined blowing process.
Representative processes	LBE, LD-KG, LD-OTB, NK-CB, LD-AB	BSC-BAP, LD-OB, LD-HC, STB, STB-P, K-BOP	OBM-S, KMS, KS

3.2. Bottom Blowing Element Types

The bottom blowing element is one of the cores of the combined blowing process, mainly including nozzle-type elements and brick type-elements. Table 5 lists the structural characteristics and performance of the bottom blowing elements [5]. Requirements for the bottom blowing system include gas-flow dispersion, uniformity and stability, and a large range of gas volume adjustments [75]. Therefore, metallurgists have developed a variety of different structural forms for bottom blowing elements.

Table 5. Comparison of the structural characteristics and performance of bottom blowing elements.

Name	Dispersion-Type Breathable Brick	Single Tube Type	Sleeve Type	Circular Seam Type
Structural Features	Multiple metal capillary tubes buried in refractories	A large diameter metal tube buried in refractories	Hollow straight circular tube and outer ring seam tube buried in refractories	Center tube filled with refractories, outer ring seam tube buried in refractories
Blockage condition	Easily blocked	Extremely easy to block	The central tube is easily clogged	Not easy to block
Element life/heat	2000–2500	100–200	2000	More than 10,000
Flow rate adjustment range	2–3 times	2–3 times	10 times	More than 10 times
Mushroom head cooling capacity	Weak	Weaker	Stronger	Strong

3.2.1. Nozzle Type Element

Nozzle type elements can be divided into the single tube type, sleeve type, and circular seam type. Among them, the circular seam type is divided into a single circular seam type and double circular seam type [76]. Different types of nozzle element terminal faces are shown in Figure 6. The early use of bottom blowing elements mainly involved the single tube type. When gas-flow velocity is lower than sound velocity, the gas-flow will be interrupted during the gas supply process, resulting in the nozzle being blocked. At the same time, due to the cooling effect of gas, the molten steel is cooled, forming an umbrella which causes the nozzle to be bonded.

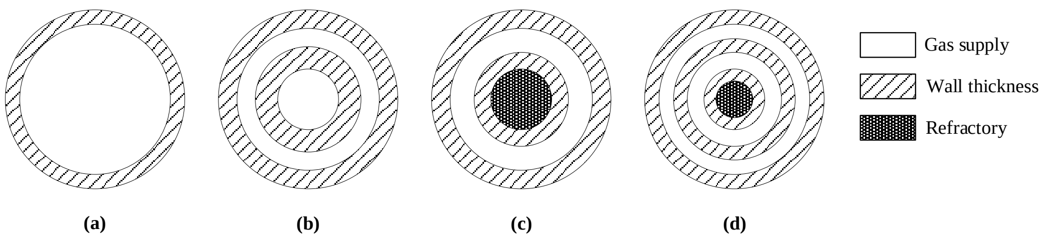

Figure 6. Diagram of different types of nozzle end face: (**a**) single tube type, (**b**) sleeve type, (**c**) single circular seam type, and (**d**) double circular seam type.

The sleeve type nozzles have been designed to increase nozzle life. Blockage is prevented by blowing oxygen through the inner tube and protective gas through the circular seam. However, it has the problem of a small range of gas volume adjustment, which cannot meet the bottom blowing gas supply requirements when refining medium and high carbon steel. The steelmaking converter mainly adopts the mode of weak bottom-blow agitation, and the bottom blowing gas is mainly inert gas with low bottom-blow intensity. Therefore, the sleeve bottom blowing element is mainly used in GOR converter refining of stainless steel and converter bottom blowing powder injection processes [77].

To solve the problem of gas volume adjustment, the Iron and Steel Research Institute has developed a circular seam nozzle. It has the advantages of a large gas volume adjustment range, good stirring effect, and small nozzle erosion and has been widely used in the steelmaking production process. The key to the circular seam type nozzle is to maintain the concentricity of double casing during processing, ensuring the stability of bottom blowing gas-flow [78]. It is easy to generate a slag-metal mushroom head after adopting the circular seam bottom blowing element, which effectively protects the bottom blowing element. After Anshan Iron and Steel adopted the circular seam bottom blowing element, the end-point [%C]· [%O] was reduced from 0.00316 to 0.00273, and the T.Fe content of slag was reduced by 1.69% [79]. After WISCO adopted the circular seam bottom blowing element, the end-point [%C]· [%O] was reduced by 0.0017, the Mn content of molten steel was increased by 0.02%, the average T.Fe content was reduced by 2.25%, the slag consumption was reduced by 4.00 kg/t, and the refining cycle was shortened by 42 s [80].

3.2.2. Brick Type Element

Brick type elements can be mainly divided into dispersion type breathable brick, gap type combined brick, straight hole type breathable brick, and porous plug brick (MHP). The structure of different brick elements is given in Figure 7. Dispersion type breathable brick is composed of dispersed micropores, and bottom blowing gas enters the molten bath from the micropores. However, its erosion resistance is poorer and service life is low. Subsequently, gap type combination brick was developed, which consists of multiple refractory bricks put together in different forms where the bottom blowing gas enters the molten bath through the brick gap. Gap type combination bricks are denser and resistant to erosion but have problems with cracking and unstable gas supply. The straight hole type breathable brick has numerous fusible metal wires embedded in the brick when it is being made. The metal wire melts to form a straight hole during the firing process, and the gas-flow enters the molten bath through the straight holes. Porous plug brick (MHP) is manufactured by burying a number of 10–150 fine metal tubes with an inner diameter of 0.1–3.0 mm in the parent refractory material. Its gas volume adjustment range is large, while the gas supply is uniform and stable. Therefore, it has been widely used in the converter production process. After continuous improvement, MHP-D porous plug brick was developed, which adds an air supply box to the outer metal tube of the brick [81].

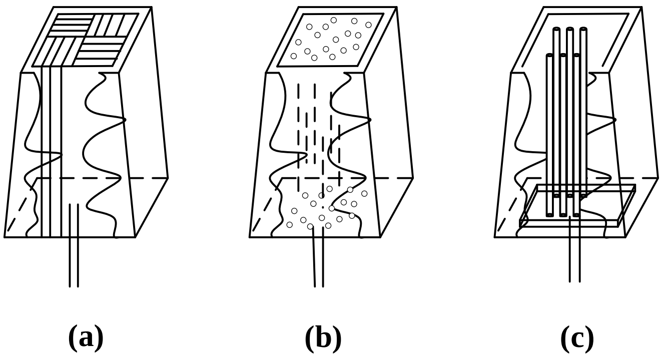

Figure 7. The structure of different brick elements. (**a**) gap type combined brick, (**b**) straight hole type, (**c**) porous plug brick (MHP).

4. Injection Medium Types and Applications

The purpose of a bottom gas supply is to strengthen molten bath stirring; therefore, there is a wide range of injection media available. Bottom blowing injection media mainly includes N_2, Ar, CO, O_2, CO_2, etc., of which N_2 and Ar are the most widely used. In addition, some powders are also used as an injection medium. Table 6 shows the characteristics of different bottom blowing gases.

4.1. Oxygen Injection

Oxygen is usually used as a top blowing medium, that is, the combined blowing process of top blowing oxygen and bottom blowing inert gas. Representative processes are LBE, LD-KG, and LD-OTB. The oxygen passes through the Laval nozzle to form supersonic jets, which impact the surface of the molten bath to form impact dents, promote the emulsification of the gas-slag-metal three-phase, and oxidize with elements such as C and P. Therefore, reasonable oxygen supply is of great significance for improving converter refining efficiency, reducing production costs and improving molten steel cleanliness. At present, converter oxygen supply intensity is usually 2.5–4.5 $Nm^3/(t \cdot min)$ in China, while the converter oxygen supply intensity can reach more than 5.0 $Nm^3/(t \cdot min)$ in Japan. The oxygen supply intensity of different capacity converters is shown in Table 7 [82].

Table 6. Different bottom blowing gas characteristics.

Gas Type	N_2	Ar	CO_2	CO	O_2
Advantages	N_2 is the cheapest of the inert gases	It not only ensures the stirring effect of the molten bath, but also has no adverse effect on the quality of the molten steel	Reacts with C in the molten bath and produces CO gas equal to twice the volume of CO_2, which facilitates the stirring of the molten bath	CO has good physical cooling properties and its metallurgical effect is comparable to that of Ar	When O_2 is used as the bottom blowing gas source, its dosage should preferably not exceed 10% of the total oxygen supply
Disadvantages	Bottom-blowing N_2 throughout the blowing process increases the nitrogen content of molten steel	Limited Ar resources and expensive Ar production equipment	Damage to the carbon gas supply elements	CO is highly toxic and has an explosion risk	Some erosion of the gas supply elements

Table 7. Oxygen supply intensity of different capacity converters.

Steel Mills	Converter Capacity/t	Oxygen Supply Intensity/$Nm^3 \cdot (t^{-1} \cdot min^{-1})$
Weiyuan steel mill	55	4.3
Taiyuan Second Steelmaking	80	4.1
LY Steel	90	4.2
Long Steel Company	120	4.5
Baosteel Second Steelmaking	250	3.33
Baosteel One Steelmaking	300	3.78

Oxygen can also be used as the bottom blowing injection medium, mainly included as part of BSC-BAP, LD-OB, K-BOP and other processes. The top oxygen supply ratio is 60–95% and the bottom oxygen supply ratio is 40–50%. At this time, the bottom gas supply element is a sleeve type nozzle, and the center tube supplies oxygen which reacts with carbon in the molten bath to produce carbon dioxide that enhances the molten bath's stirring effect. The ring seam supplies natural gas, LPG, etc., as the coolant. However, when oxygen is used as the bottom blowing injection medium, the life of the bottom blowing element is relatively shorter.

4.2. Inert Gas Injection

The inert gas injected in the converter steelmaking process is mainly N_2 or Ar. N_2 is a by-product of oxygen production that is cheap and does not react with molten steel elements. It is one of the widely used bottom blowing gas sources at present. However, blowing N_2 will increase the nitrogen content of steel and affect steel quality [83]. Bottom blowing Ar can not only ensure the stirring of the molten bath, but also does not have any adverse effect on the quality of molten steel. It is the most ideal bottom blowing stirring gas source at present. However, Ar is expensive and the refining cost is high.

Refining of plain carbon steel and other steel refining usually involves injection of N_2 throughout the whole process; steel refining of pipeline steel and automobile plates injects Ar, and alloy structural steels use N_2-Ar switching injection mode. Sun et al. [84] studied the effect of the N_2-Ar switching injection mode on the quality of molten steel and found that with the extension of the N_2-Ar switching time node, the amount of nitrogen added to molten steel gradually increased. When the oxygen blowing ratio was within 56%, the nitrogen absorption rate was very small at this time, and the change in the N_2-Ar switching node had less effect on the nitrogen content of molten steel.

4.3. Carbon Dioxide Injection

CO_2 is not only easy to obtain but also has a good physical cooling effect and chemical cooling effect. In addition, carbon is oxidized when CO_2 enters the molten bath, which doubles the volume of the gas molecules and facilitates molten bath stirring [85].

At the early stage of refining, the temperature is low, and silicon and manganese are preferentially oxidized when CO_2 is blown; in the middle of refining, where the decarburization rate is the highest, CO_2 is mainly involved in the decarburization reaction of the steel, and the decarburization rate of the molten bath is greater when CO_2 is blown than other inert gases; at the end of refining, CO_2 mainly reacts with Fe [86]. A mixed injection of CO_2-O_2 to a basic oxygen furnace was applied to enhance dephosphorization, and promising results were reported [87]. Feng et al. [88] studied the change in the molten bath flow field with a CO_2-O_2 mixed injection and found that the jet convergence point advanced and the jet impact area increased with increasing CO_2 and O_2 flow rates. Han et al. [89] found that CO_2 injection could reduce dust generation, increase the CO concentration of the converter gas, improve dephosphorization, and decrease nitrogen content. Zhu et al. [85] found that, in the CO_2-O_2 mixed injection process, CO_2 conversion of up to 80% or more could be obtained by controlling the CO_2 ratio, with significant energy savings.

The authors conducted industrial tests with CO_2 injection on a 30 t converter and found that the T.Fe content and phosphorus content distribution decreased by 5.94% and 0.007%. In addition, the author proposed a new dephosphorization process, in which CO_2 was mixed in an oxygen jet, and conducted industry tests in a 300 t dephosphorization converter [90]. It was found that using CO_2 as the dephosphorization oxidant could control the molten bath temperature and obtain a better dephosphorization effect.

4.4. Powder Injection

Injecting powder can significantly improve the converter's slag-metal interface area and impurity element removal rate, which can accelerate lime melting. Injected powders are mainly lime powder and iron ore powder. The powder is usually injected into the molten bath, with bottom blowing inert gas as a carrier or through the top blowing oxygen lance [91].

In 1952 and 1953, oxygen top blowing converters were built and put into production at the Linz and Donawitz plants in Austria, which became known as the LD process. Compared to the Bessemer process with acidic or alkaline bottom blowing air, the LD converter could refine hot metal with high manganese and medium to high phosphorus content, and the nitrogen content of steel was much lower [92]. Therefore, the ductility of steel was significantly improved, and the products could be widely used in the rapid development of the automobile industry at that time. Isaide developed the LD-OLP process and the LD-AC process was developed by the French Metallurgical Research Center, both of which used an oxygen lance to inject lime powder into the converter to smelt high-phosphorus hot metal [93]. In the 1980s, metallurgists conducted industrial tests of dephosphorization from converter powder injecting. The results [94,95] showed that the blowing process was stable and that the metal yield was high when injecting powder for dephosphorization, and the dephosphorization rate of molten steel increased with the increase in powder injection. Tang et al. [96,97] studied molten bath flow characteristics in the process of top blowing limestone particles and bottom blowing lime powder respectively. They concluded that the lance height should be reduced when top blowing powder, and the powder penetration ratio increased with the increase in solid-gas ratio and powder particle size. Liang et al. [98] conducted a water simulation experiment of bottom blowing oxygen and lime powder and found that powder injecting could promote molten bath stirring; the powder diffusion rate increased with the increase in bottom blowing carrier gas. Zhou et al. [99,100] found that bottom blowing O_2-CaO improved reaction efficiency; the amount of slag per ton was reduced by 11.2 kg, and the phosphorus content was decreased by 0.005%. The authors [101] conducted experiments with a 150 t converter on the subject of vanadium extraction through powder injection and studied the stirring effect and impact characteristics of powder injecting. It was found that powder injecting improved the kinetic and thermodynamic conditions of the vanadium extraction reaction and promoted the vanadium extraction reaction.

5. Development Direction of Injecting Technology

Based on the traditional supersonic oxygen lance, metallurgists have designed different types of oxygen lance to meet different refining requirements, and achieved good results. However, it is necessary to further optimize the nozzle structure and strengthen nozzle cooling, as well as apply the newly designed oxygen lance in industrial tests to check the performance of the oxygen lance. Optimizing the bottom blowing element's arrangement and increasing the bottom blowing element's life are the current development directions of bottom blowing technology. In terms of injection medium, in addition to using conventional gases such as N_2 and Ar, it is necessary to further find a suitable bottom blowing source. Using CO_2 as a carrier gas to inject powder into converters may be a good bottom blowing process.

5.1. High Efficiency

Increasing gas injection intensity and strengthening molten bath stirring have become the main measures used to promote the efficiency of converter steelmaking. At present, the large capacity of the converter has become inevitable. To meet the efficient production need for the large converters, metallurgists will further optimize the oxygen lance nozzle structure and reasonably arrange bottom blowing elements to promote the realization of high-flow oxygen supply technology and high-intensity bottom blowing technology [102,103]. On the one hand, improving the oxygen supply intensity to above 4.5 $Nm^3/(t \cdot min)$ could shorten the refining time and improve production efficiency. On the other hand, increasing the bottom blowing intensity to above 0.2 $Nm^3/(t \cdot min)$ could further strengthen molten bath stirring, and reduce the dead zone area of the molten bath.

5.2. Reduce Environmental Burden

With the implementation of environmental protection guidelines and policies, the steel industry must also move towards green development while producing efficiently. The greening of converter injection technology should not only achieve clean production, but also reflect the idea of ecological industry and the circular economy, that is, "reduce, reuse, and recycle". The CO_2 emitted during the steel production process is recovered and used as a source of top and bottom blowing gas [89,104], reducing CO_2 emissions while saving energy. In addition, the amount of flue gas generated during the converter blowing process increases with the application of converters with high-flow oxygen supply technology. Therefore, dust removal efficiency should be further improved to realize the green production of converter steelmaking.

5.3. Long Life

The long life of injection elements ensures the high efficiency of converter injection technology. To realize the long life of oxygen lance nozzles, casting nozzles with a short life have been gradually replaced by a forging nozzle, and the lifespan can currently reach more than 500 heats. On the one hand, the processing method, material, internal structure, and water-cooling measures of the oxygen lance nozzle need to be further optimized to improve the life of converter oxygen lance nozzles [105]. On the other hand, the life of the bottom blowing element should be prolonged by improving the material of the bottom blowing element, adjusting the nozzle structure, and reasonably arranging the bottom blowing element [106].

6. Conclusions and Outlook

The steel industry is an essential pillar of national industrialization and plays an important supporting role for related industries. Nowadays, under the new situation of structural adjustments in the steel industry, it will become the key development direction of converter steelmaking in the future as the industry seeks to further build a clean steel production platform that is highly efficiency, green, and intelligent. Based on this, accelerating the technological innovation of converter steelmaking injection, especially improvements and breakthroughs related to efficiency, green production methods and long life technology, will play an important role in promoting the transformation and improvement of the steel industry towards green and intelligent technology.

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