Approach to Improvement of Steel Quality through Suitable Application of Refractories for Continuous Casting

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Abstract

Refractories for continuous casting such as the submerged entry nozzle and gas-blowing upper nozzle considerably influence steel quality. In this article, a suitable submerged entry nozzle structure that allows desirable molten steel flow in the mold, and suitable properties of the gas-blowing upper nozzle in terms of inclusion floating, improving seal-ability of gasket of ladle shroud are described. By improving these refractories for continuous casting, it is possible to improve steel quality as well as refractory durability.

1. Introduction

Most of steel products, such as plate, bar, H-steel, and so on, are manufactured by continuous casting (hereinafter referred to as CC) method. In Japan, the CC rate for all steel production has increased according to its excellent productivity and exceeded 90% in 1983. Recently, almost 100% of the steel products are made by the CC process[1].

Fig.1 summarizes CC facilities and refractory applications. Roughly speaking, refractories applied for the CC process are classified into the following three categories according to function. Molten steel-pouring refractories such as submerged entry nozzles (hereinafter referred to as SEN) and ladle shrouds (hereinafter referred to as LS), gas injecting refractories such as gas injection insert nozzles, and liquid flow rate controllers such as stoppers and slide valve (hereinafter referred to as SV) plates. CC is the process that determines steel slab quality. Steel-pouring refractories and gas injecting refractories play important roles such as eliminating steel pollution from air (re-oxidation and/or nitrogen pick up), rejecting non-metallic inclusions, and optimizing fluid flow in the casting mold, which strongly influences the quality and yield of steel slab.

Recently, increase in high grade steel production and strict quality control requires further improvements of refractory functionalities. This article describes our CC refractory technologies comprehensively in terms of the functionality.

2. Steel Slab Defects Occurred in CC Process and Their Causes

Cast steel slabs occasionally show some kinds of defects. Slab defects are categorized as contamination, cracking, and deterioration in cleanliness, which are caused by various factors. Therefore, accurate evaluation of their causes according to the careful investigation of defects and applications of suitable countermeasures is necessary in order to reduce slab steel defects. Fig.2 is a summary of typical slab defects and their causes.

Contamination consists of non-metallic inclusions and gas bubbles. The non-metallic inclusions come from deoxidation products, which are composed of alumina and aluminous oxides, and mold flux. Ar gas, which is injected for the sake of trapping and flotation separation of non-metallic inclusions, is the origin of bubble contamination. Inappropriate fluid flow in the casting mold induces contamination. Fig.3 exemplifies fluid flow in the casting mold simulated by water-model experiments. (A) shows a liquid flow biased toward left outlet port. Such biased flow promotes liquid surface level fluctuation and inclusion trapping on a specific side, resulting in contamination. (B) of Fig.3 compares flow behaviors of the liquid drained from an unused SEN and a used SEN, which had been clogged during commercial application. The nozzle

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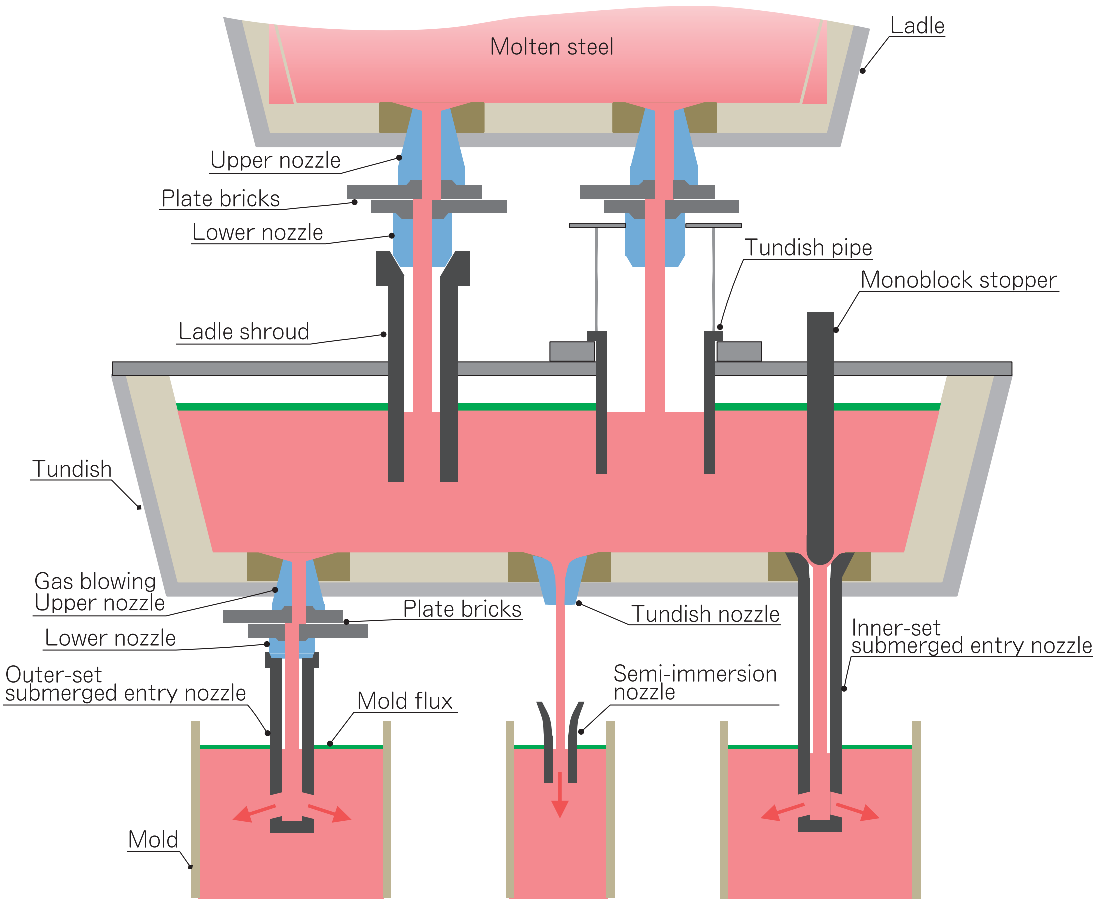


Fig.1 Schematic illustration of facilities and refractories for continuous casting.

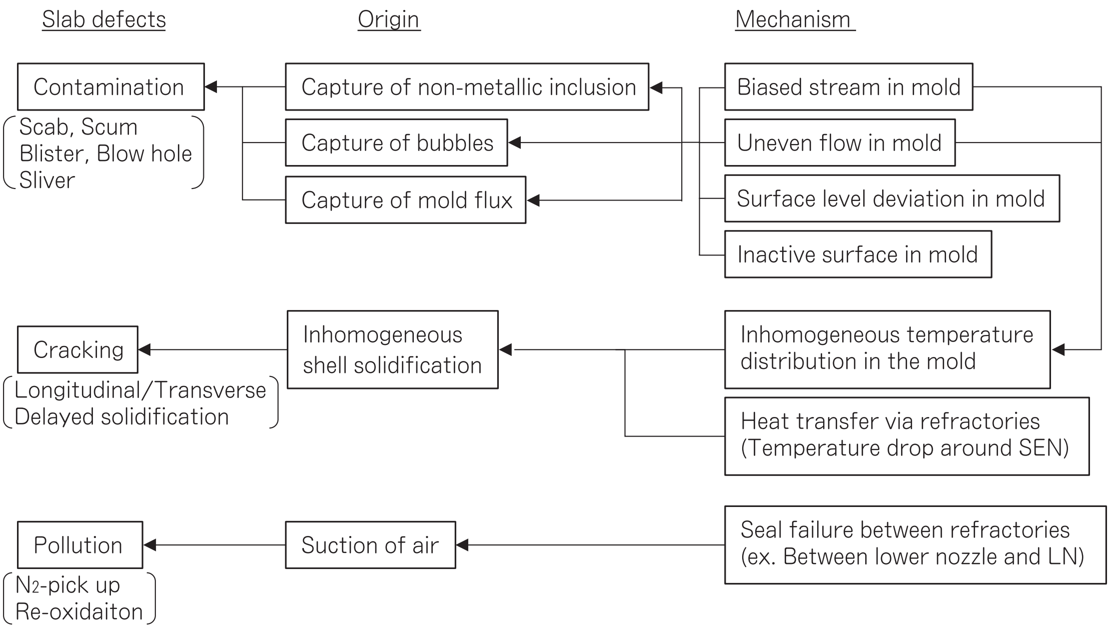


Fig.2 Kinds of slab defects and their causes.

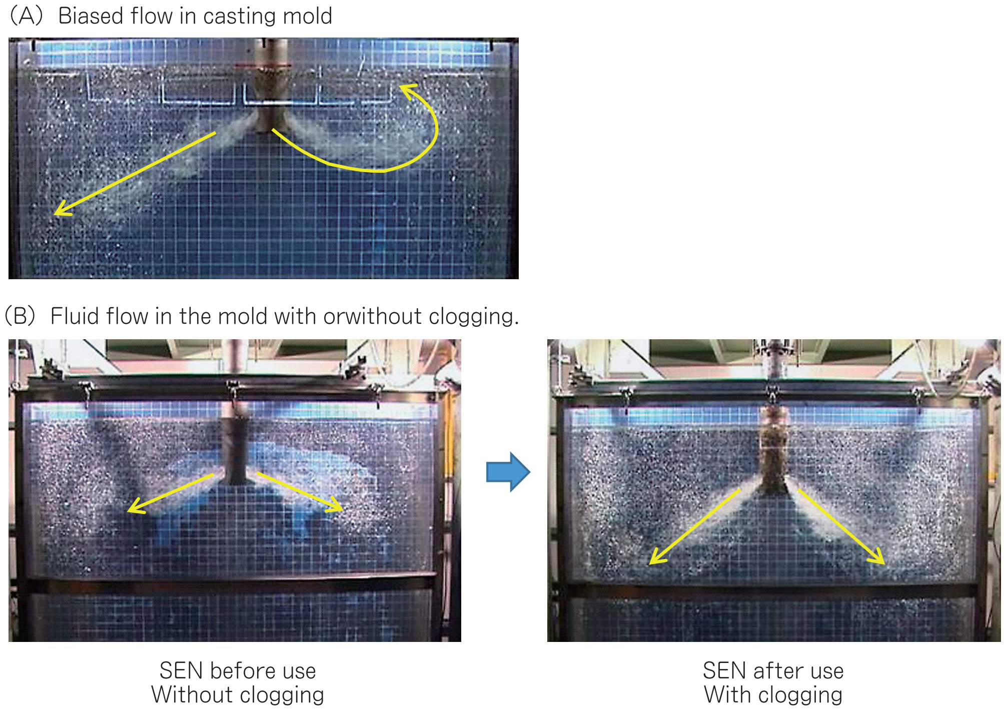


Fig.3　Examples of fluid flow in the mold simulated by water-model experiment.

clogging occurred as a result of adhesion and growth of non-metallic inclusions. The downward stream caused by clogging tends to entrain non-metallic inclusions, resulting in contamination. While Ar gas purging from the insert nozzle is an effective measure for trapping and flotation separation of non-metallic inclusions, inadequate gas purging promotes bubble contamination.

Most of cracking can be attributed to inhomogeneous solidification of molten steel. The biased flow, as shown in Fig.3(A), increases temperature deviation in the casting mold, which induces inhomogeneous solidification.

Steel pollution such as re-oxidation and/or nitrogen pick up is caused by air suction via interface between LS and lower nozzle. This is attributable to deterioration of seal-ability.

In this article, therefore, recent innovative improvements in the SEN, gas blowing insert nozzle, and gasket between LS and lower nozzle of steel ladle are described.

3.　Improvements in CC Refractory Functionalities

3. 1　Bore shape of SEN

In the case of casting though a half-opened SV, a narrow flow channel tends to be formed on the bore surface of SEN, resulting in uneven steel supply that sometimes induces steel quality deterioration. In order to achieve a uniform steel supply, applications of annular-step SEN and/or mogul SEN were found to be effective. Fig.4 schematically shows the liquid flow on the surface of the SEN bore. The stream branches at the corner of the step or moguls, and is distributed evenly on the bore surface. This was observed by water-model experiment. It clarified the suppression of the biased flow in the SEN and mold, resulting in reduction of liquid surface level deviation. Moreover, stable bubble floatation and uniform flow rate distribution at the outlet port were recognized. Fig.5 demonstrates the flow rate distributions evaluated by water-model experiment. Obviously, a uniform flow rate distribution that eliminates a stream toward the inside is achieved for the mogul SEN. The effectiveness of these

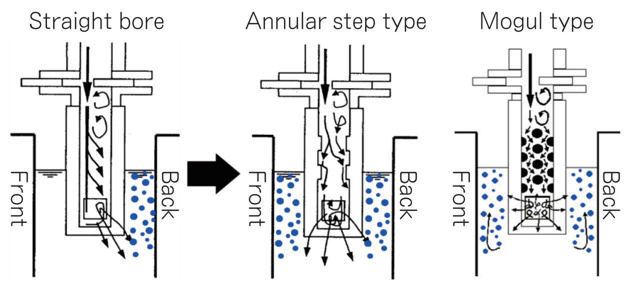


Fig.4　Influence of bore shape on fluid flow in SEN.

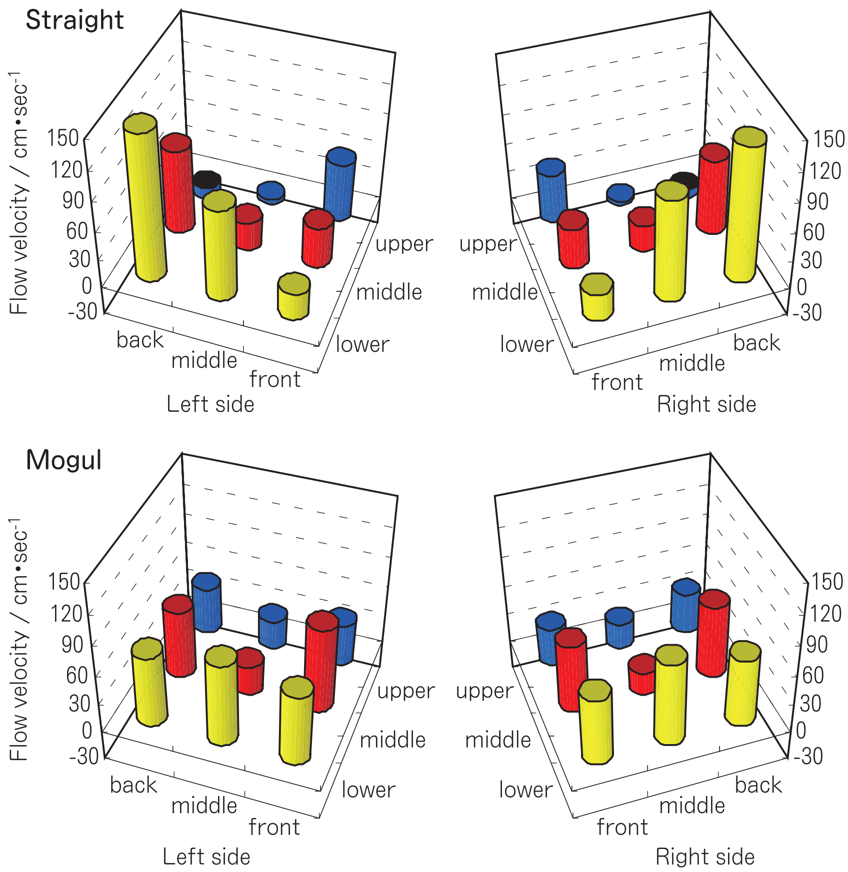


Fig.5 Distribution of average flow velocity at outlet port in water model experiment.

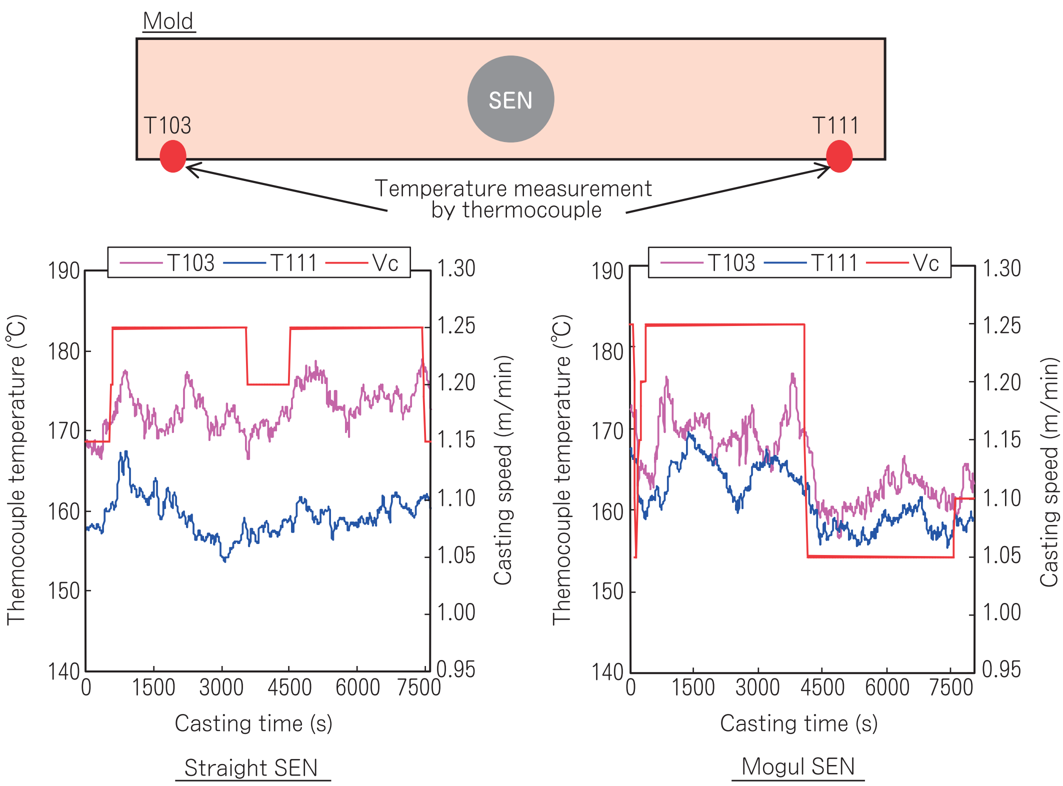


Fig.6 Trends of mold temperature measured by thermocouples located at the opposite ends of the mold wide face during casting.

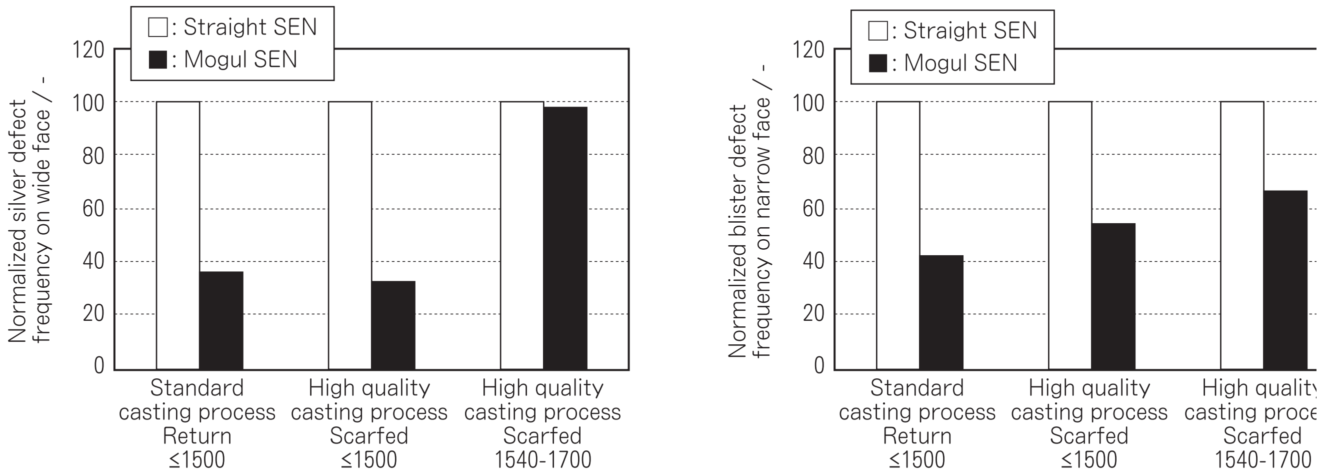


Fig.7　Influence of Mogul SEN application on defect frequency.

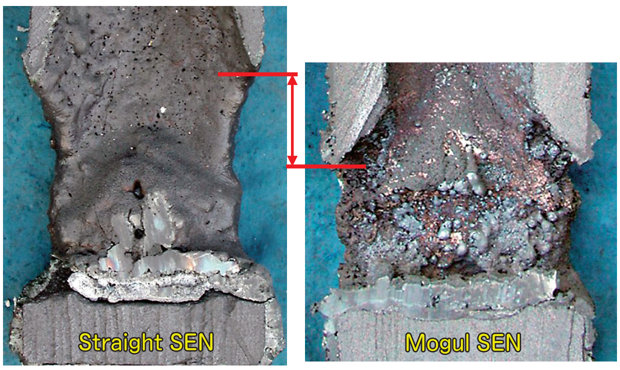


Fig.8　Cut section of Straight bore SEN and Mogul SEN after use.

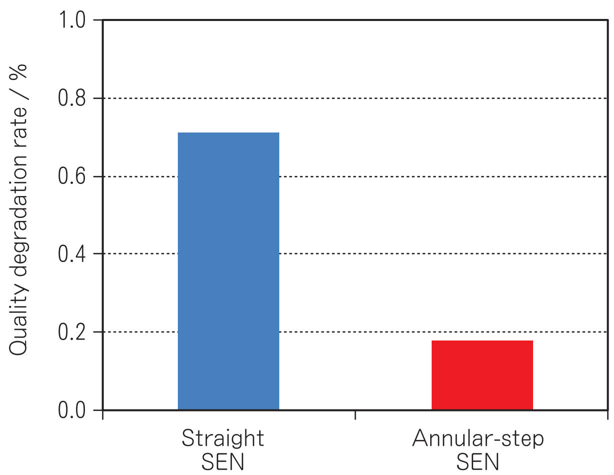


Fig.9　Influence of Annular-step SEN application on outlet port corrosion and quality degradation rate.

unique shape SENs was validated by many commercial applications.

Fig.6 shows the influence of the mogul SEN on the suppression of biased flow[2]. The degree of bias was evaluated by the temperature difference between thermocouples embedded in opposite ends of the wide faces of the casting mold. In comparison with a casting operation using a straight bore SEN, which showed 14℃ difference in temperatures, a considerably smaller temperature difference (4℃) was evaluated for casting using a mogul SEN. This is considered attributable to symmetrical fluid flow in the casting mold caused by uniform steel supply from two outlet ports. The same effects are also observed for annular-step SEN[3].

Fig.7 shows the effects of the mogul SEN on the frequency of sliver and blister defects[4]. The steel mill uses a bow type caster which has less ability of floatation separation of inclusions since there is no vertical part. Thus, it is assumable that un-separated inclusions tend to be trapped just below the upper solidified shell and cause blisters and sliver defects. According to that assumption, the mogul SEN was used in order to reduce biased flow that is accompanied by entrainment of inclusions and bubbles. Fig.7 shows the results of a six month trial evaluated by a surface inspection system. Application of mogul SEN reduced sliver defects by half and blister defects by one-third to half.

Fig.8 shows the influences of the application of the annular-step SEN on outlet port corrosion. The inward flow toward the SEN outlet port induces mold flux contamination and promotes corrosion of the outlet port. Naturally, it is assumable that refractory substances, which are derived as a result of corrosion, cause slab defects. Fig.9

compares grade reduction rate according to sliver defects between straight bore SEN and annular-step SEN. By application of the annular-step SEN, the inward flow was eliminated, resulting in reductions of outlet port corrosion and slab defect frequency.

As discussed above, optimization of fluid flow in the casting mold, which improves slab quality, is achievable by utilization of a functional SEN such as the annular-step or mogul type. According to the effectiveness, they have been widely adopted to many slab casters and bloom casters in association with anti-clogging material applications. The anti-clogging materials will be described later.

3. 2 Outlet port shape of SEN

Predictably, shape, angle and number of SEN outlet ports considerably influence on molten steel flow in a casting mold. An intensive downward stream generated by downward-oriented outlet port stabilizes liquid surface movement. Thus, it is effective to operations in which liquid surface level fluctuation is permanently large and/or high throughput operation. However, excessively intensive downward stream delivers inclusions and/or bubbles deeply in the partially solidified slab and causes slab defects. On the other hand, SENs with lower angle outlet ports, i.e., closer to the horizontal direction, is an advantageous status in terms of reduction of entrainment of inclusions and/or bubbles as well as efficient heat supply to the liquid surface, which is a favorable status for improving slab surface quality. However, if the accompanying liquid surface level fluctuation is excessively large, productivity will deteriorate.

Fig.10 demonstrates the spreading outlet port of which the horizontal width of the port increases toward the outside. A spreading stream exiting from this outlet port enables flow speed deceleration without throughput reduction. In addition, it decreases upward and downward flow speeds at the narrow surface side without changing outlet port angle as indicated in Fig.11. It is considered to be effective for suppressing entrainment of inclusions as well as liquid surface level fluctuation. Fig.12 shows the effectiveness of the spreading outlet port stream on slab solidification. Flow speed deceleration effectively suppressed the delayed solidification around the slab corner, resulting in reduction of corner cracking frequency.

While it is well-known that a swirling flow induced by electro-magnetic stirring (hereinafter referred to as EMS) improves slab quality, there still are many EMS-uninstalled casters. Thus, a bending-shape outlet port, which is designed to generate swirling flow, was

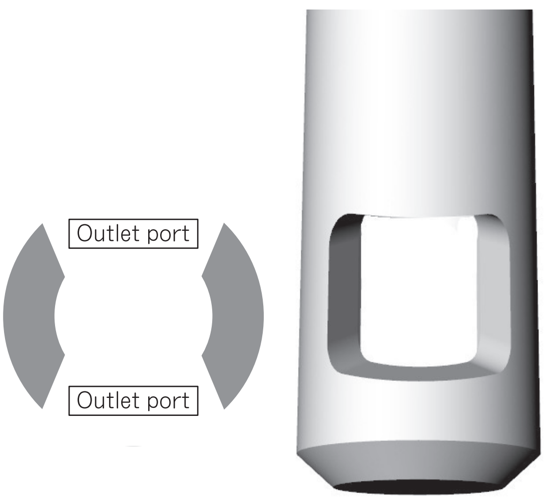


Fig.10 Schematic diagram of spreading outlet ports.

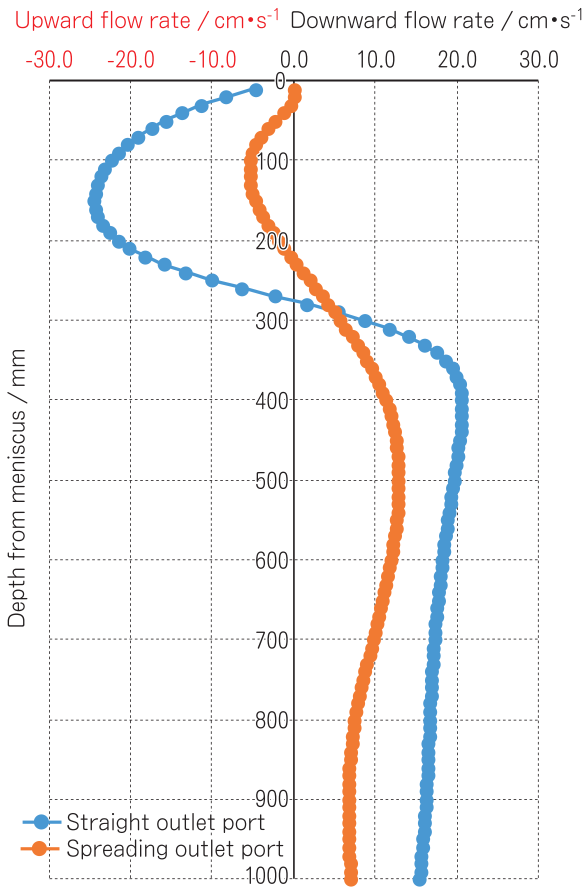


Fig.11 Flow rate distribution along narrow face of mold evaluated by CFD calculation.

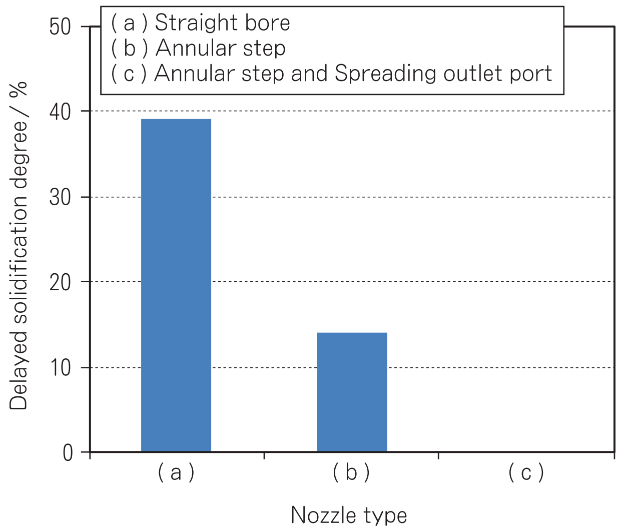
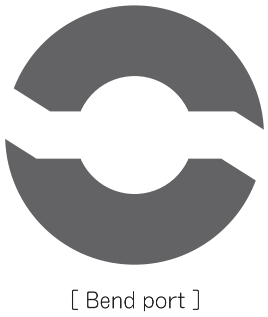


Fig.12　Effect of nozzle type on inhomogeneous solidification of shell around the corner.

developed[5]. Fig.13 is a schematic diagram of bend port and swirling flow generation validated by the water-model experiment of which light beads were floated for the sake of visualization. Obviously, stable swirling flow was recognized. Fig.14 shows the influence of bending port SEN application on the bleeding detect rate of a slab associated with the external view of a used bending port SEN. An obvious reduction in bleeding defect frequency is considered attributable to homogeneous formation of the solidified shell resulting from uniform heat supply through adequate swirling. No trace of outlet port corrosion or clogging indicates that the effectiveness had been maintained until casting sequence completion.

As described above, it is necessary to optimize SEN shape design taking customer's requirements and operation conditions into account.



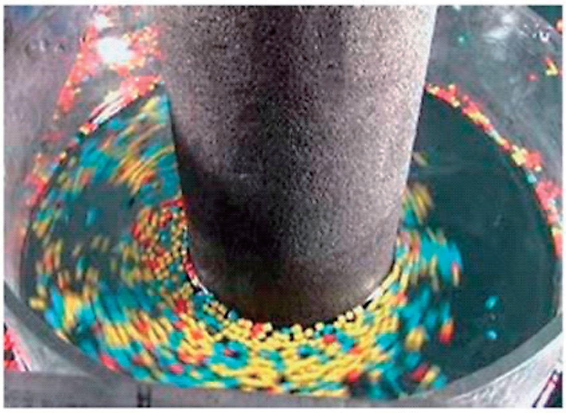


Fig.13　Swirling flow generated by “Bend port” SEN.

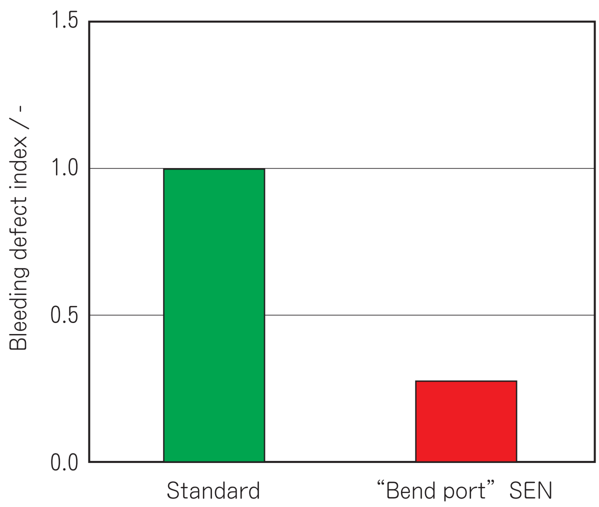


Fig.14　Appearance of “Bend port” SEN after use and comparison of the bleeding defect rate.

3. 3 Anti-clogging materials for SEN

As shown in Fig.3, SEN clogging considerably influences on flow in the casting mold. Thus, clogging should be eliminated from the viewpoints of casting sequence extension and improving slab quality. Clogging mechanisms are hypothesized as follows:

(1) Reaction between Al in steel and substances included in SEN

CO(g) and SiO(g), which are formed as a result of a reaction between SiO_2 and C in SEN material, transfer to the inner surface of the SEN bore and react with the Al in the steel to form aluminous oxide network on the SEN surface as shown in Fig.15.

(2) Collisions and adhesion of non-metallic inclusions

In the vicinity of the SEN inner surface where fluid flow is negligible, inclusions float slowly and attract each other to form agglomerations that tend to collide with and adhere to the inner surface of SEN. The surface configuration considerably affects the adhesion easiness. The agglomerations which contact the wall attach easily to the rough surface, which is formed by SiO(g) evaporation and carbon dissolution. Furthermore, poor wettability of the SEN surface to molten steel promotes adhesion since a pushing force is imposed to the agglomerations as shown in Fig.16.

On the basis of the above hypothesis, it was understood that installation of carbon-free materials as liner on the bore surface is effective since SiO_2 reduction and carbon dissolution can be suppressed so as to improve surface smoothness, which is desirable in terms of inclusion adhesion. Additionally, improvement of wettability is considered to be effective. It is achievable by in-situ formation of a surface layer that includes adequately controlled molten steel-wettable liquid phase. Table 1

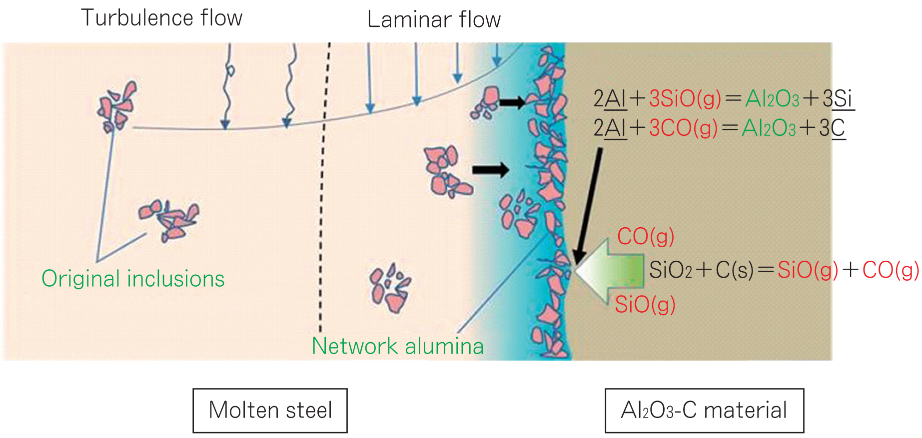


Fig.15 Schematic illustration of alumina adhesion.

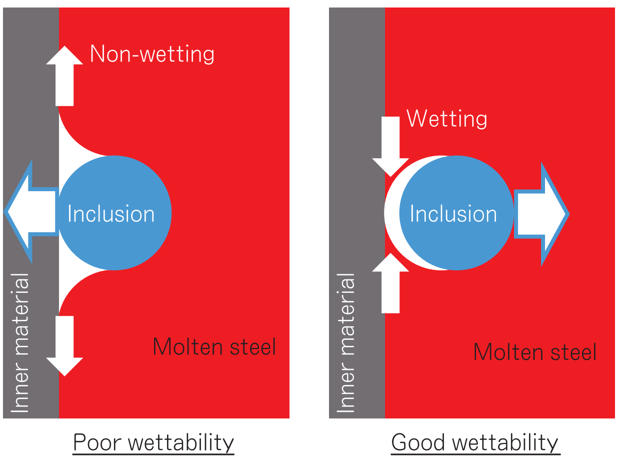


Fig.16 Influence of wettability of a SEN refractory to molten steel on inclusion adhesion.

Table 1 Properties of anti-clogging materials

Type	Unreactive			Reactive		
Material code	AS	A	Sp	AS	Sp	CZ-C
Apparent porosity / %	22.5	23.0	21.5	20.0	18.5	14.0
Bulk density / g・cm^{-3}	2.40	2.90	2.70	2.10	2.75	3.05
Chemical composition / mass%						
Al_2O_3	66	96	70	41	64	-
SiO_2	27	-	-	56	4	1
CaO	-	-	-	-	3	22
MgO	-	-	26	-	24	-
ZrO_2	-	-	-	-	-	49
C	-	-	-	-	-	23

A : Al_2O_3, S : SiO_2, Sp : Spinel, CZ : $CaOZrO_2$

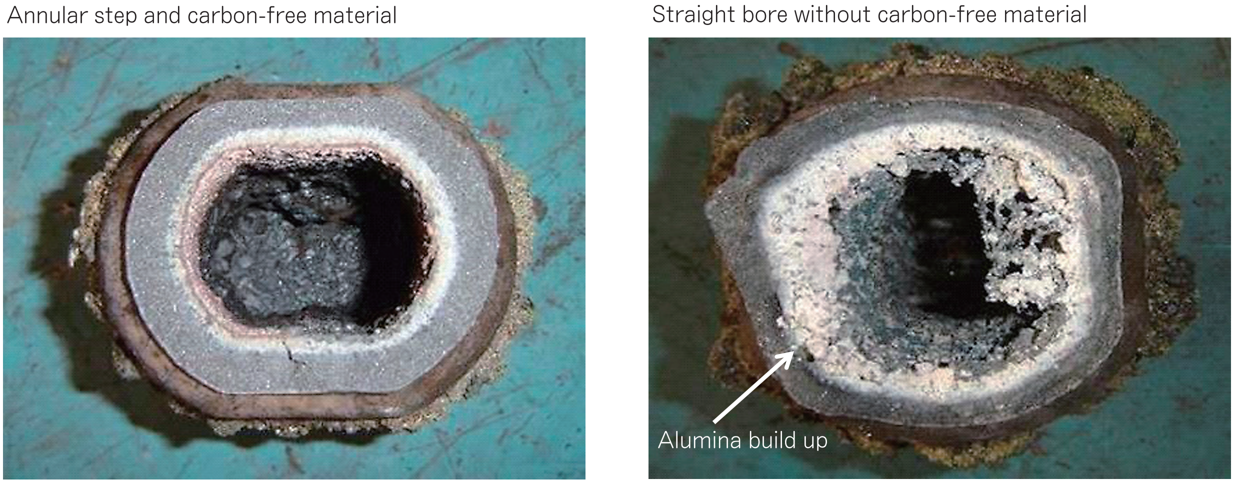


Fig.17 Cross section of SEN used for 6 heats of low carbon steel casting.

provides the typical properties of anti-clogging material for the liner. The steel-reactive type is a material in which the contained SiO_2 reacts with the Mn in the steel to form a steel-wettable reaction layer. Spinel material adequately contains a flux component, which allows the steel-wettable surface layer. $CaO-ZrO_2-C$ (CZ–C) is a steel-reactive type carbon-including material. Effectiveness of this material on suppression of clogging has also been confirmed by commercial applications. Since it exhibits larger thermal expansion, sufficient pre-heating is necessary for CZ–C.

As described in subsection 3.1, application of an anti-clogging material liner associated with flow controllable bore structure effectively suppresses the clogging. Fig.17 shows the effect of combined application of a carbon-free liner and annular-step bore on clogging. Thanks to the suitable combination, prolongation of service life and reduction in steel quality degradation were obtained simultaneously.

Clogging occurs not only at the bore but also at the outlet port. Outlet port clogging is attributed to the liquid flow out behavior which includes a stagnant area. The stagnation is caused by compensation of the outward flow by the inward flow, which occurs as a result of inappropriate port shape. This phenomenon was confirmed by calculations utilizing computational fluid dynamics (CFD) and/or water-model experiment. Stagnant area shown in Fig.18(a) corresponds to the area on which inclusions tends to adhere. Hence, elimination of stagnation by applying appropriate port shape as shown in Fig.18(b)

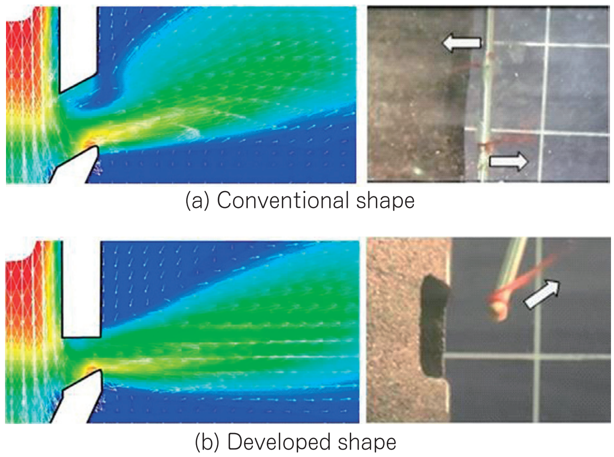


Fig.18 Fluid flow in the vicinity of outlet port demonstrated by CFD calculation and water model experiment.

is considered to be effective for suppressing outlet port clogging[6].

3. 4 Improvement of gas blowing insert nozzle

Many steel mills adopt inert gas (Ar) blowing from tundish insert nozzle. Blew gas bubbles are dragged down through SEN and float up in the casting mold. The purpose of gas blowing is as follows.

(1) Suppression of non-metallic inclusion adhesion to bore surface of insert nozzle and SEN (suppression of clogging)

(2) Promotion of floatation separation of inclusions in the mold

(3) Heat supply to liquid surface in the mold by activation of liquid surface (surface solidification inhibition)

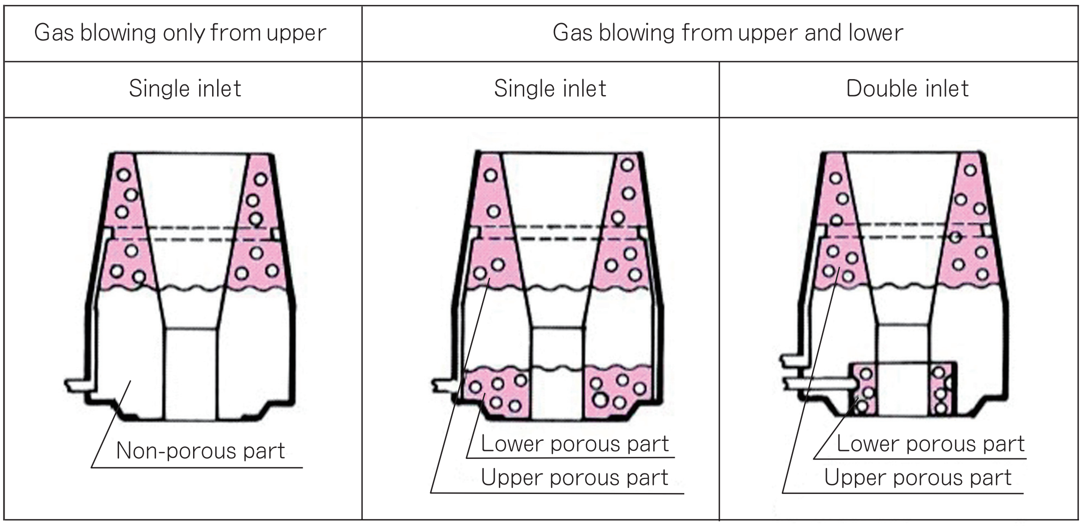


Fig.19 The structure of various insert nozzles for gas injection.

As the bubble-dispersed liquid steel flows down along the bore surface of the nozzle, bubbles capture the non-metallic inclusions, resulting in suppression of adhesion of non-metallic inclusions. In the casting mold, the dispersed bubbles float up capturing the collided non-metallic inclusions, thus, floatation separation of the inclusions is promoted. The continuous floatation of bubbles stirs the liquid steel in the mold so as to inhibit surface solidification.

In spite of the above favorable advantages of gas blowing, it causes slab defects if bubbles are trapped in the slab. Thus, blowing of a minimum amount of inert gas to satisfy the above three factors is recommended. Fig.19 shows an example of a gas blowing insert nozzle configuration. A suitable arrangement of a simultaneously fabricated porous part and dense part enables the uniform gas blowing with minimum gas volume. Furthermore, selective gas blowing technology, of which intensive gas flow area can be adjusted to the easy-clogging zone, allows effective clogging suppression.

The pore diameter of a porous medium determines bubble diameter. As described in Strokes' equation, floating speed becomes higher as bubble diameter increases. Hence, big bubbles float around the SEN and small bubbles are delivered to the narrow face of the mold. It is possible that fine bubbles that collides the narrow face flow down deep into the mold along with the molten steel stream and induce slab defects. Table 2 qualitatively summarizes bubble size and functionality of a gas blowing insert nozzle. As described above, careful selection of porous medium taking operation into account is important. Generally, materials with an average pore diameter of 20-30μm are applied. Empirically, application of large pore diameter insert nozzle tends to improve slab quality. This is considered attributable to immediate floatation of purged bubbles.

Table 2 Influence of bubble size on functions of insert nozzle

Functions	Bubble size	
	Large	Small
Anti-clogging effect according to inclusion trapping	Negative	Positive
Inclusion-floating effect	Positive	Negative
Fluid surface activation effect	Activates nozzle surroundings	Activates narrow face of the mold

Bubble diameter influences nozzle clogging as well. Inclusion capturing efficiency is improved as bubble diameter decreases since the increase in number of bubbles and overall specific surface area increase the probability of collision with the non-metallic inclusions. Additionally, according to the calculated result, as demonstrated in Fig.20, small bubbles flow down along the surface of SEN bore. Thus, blowing smaller diameter bubbles is desirable in terms of clogging suppression.

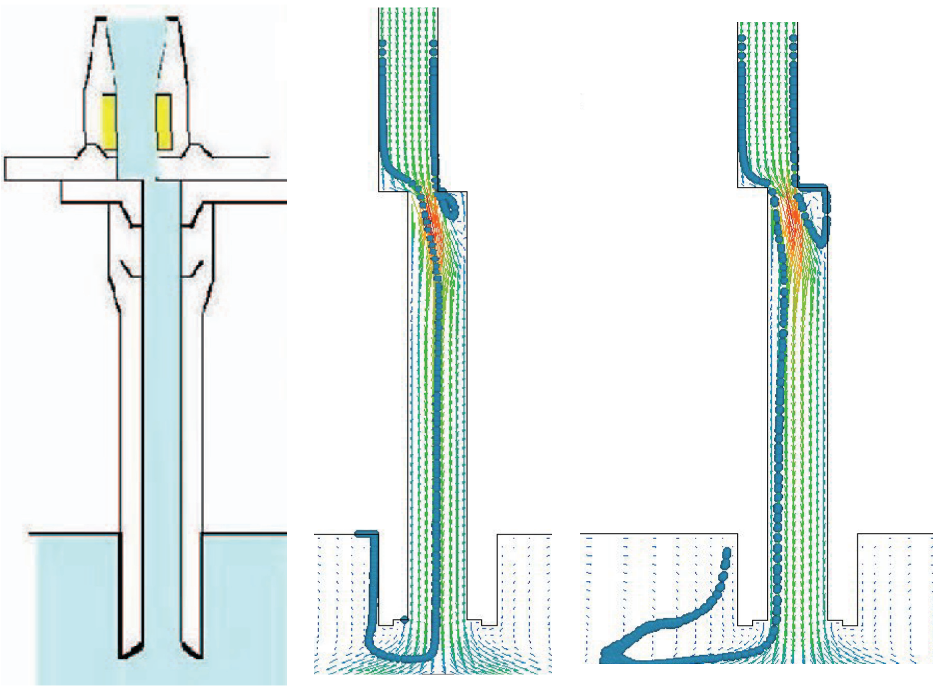


Fig.20 Difference in bubble passing routes according to bubble size.

3. 5 Double layer gasket for LS suppressing N_2 pick up

To the interface between lower nozzle of steel ladle and LS, application of a gasket as a joint material is necessary in order to suppress slab quality deterioration according to air suction and refractory damage. Since the LS is used through several casting, easy removability of gasket is important. Fig.21 shows refractory wear induced by air suction via interfacial joint. If the gasket sticks the joint face of the LS tightly, complete removal will be difficult, resulting in formation of the used gasket layer, which adversely affects the air seal.

Air suction causes not only refractory wear but also deterioration of steel cleanliness according to nitrogen pick up. For the sake of air suction suppression, application of

"Seat part of lower nozzle (After use)" "Seat part of long nozzle (After use)"

Fig.21 Example of corrosion caused by air suction.

"Double layer gasket"

"Seat part of long nozzle (After use)"

Fig.22 Application of double layer gasket.

double layer gasket is favorable. It is the gasket consists of deformable material, which improves the seal-ability, and carbon sheet, which improves removability. Fig.22 shows the external image of the gasket before and after use. Fig.23 exemplifies effectiveness of the gasket on nitrogen

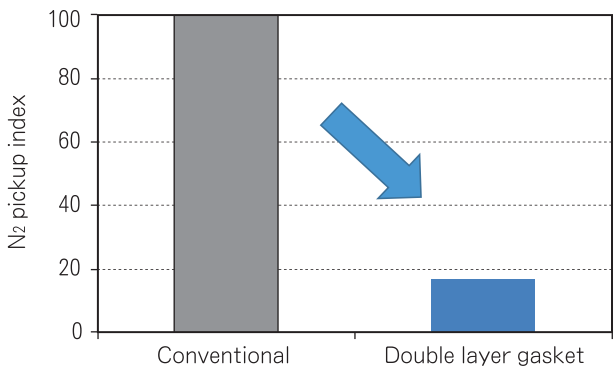


Fig.23 Effectiveness of double layer gasket.

pick up suppression. Thanks to the double layer gasket application, improvements of LS joint face durability and steel cleanliness were obtained.

4. Conclusion

In terms of quality improvement of steel slabs produced through the continuous casting (CC) process, refractories for CC equipment play important roles. In this article, optimization of submerged entry nozzle (SEN) structure, controlling of bubble diameter blowing from insert nozzle, and improvement of seal-ability of the gasket installed between lower nozzle of steel ladle and ladle shroud were introduced from a functional point of view. Table 3 summarizes the recent developments of refractories for the CC process and expectable achievements.

Optimization of SEN shape enables the desirable fluid flow in the casting mold. Applications of SEN with unique

Table 3 Efforts for improving CC refractories and expected achievements

Items	Efforts	Achievements
SEN	Bore shape ex. Annular type, Mogul type Outlet port shape ex. Spreading shape, Rectangular shape Anti-clogging materials ex. Non-carbon, Steel-Wetting	Suitable flow in the mold Homogenous heat supply -> Reduction of contamination -> Suppression of slab cracking Suppression of clogging -> Long service life -> Reduction of quality degradation rate
Gas-blowing upper nozzle	Optimized gas purging ex. Position of porous material, Bubble diameter	Promotion of inclusion floating Promotion of inclusion trapping Liquid surface activation in mold
Long nozzle	Optimized gasket structure Sealability, detachability	Reduction of Nitrogen pick-up Prolonging service life

bore shape such as annular step or mogul surface is increasing according to the effective improvement of slab quality, particularly for high speed caster. In addition, combination of suitable structure and anti-clogging liner material successfully decreases SEN clogging, resulting in increase in casting sequence as well as improvements of slab quality and operational stability.

We will continue to engage in CC refractory development in order to improve steel quality as well as operation efficiency.

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