Bulletin — 2025 — pp. 58—67

RHI MAGNESITA

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Design and Implementation of High-Performance Submerged Entry Nozzles for Thin and Medium-Thickness Slab Casting

Thin and medium-thickness slab casting operations impose unique demands on submerged entry nozzle (SEN) designs. These casters typically involve narrow cross-sections, funnel-shaped moulds (for thin slab), high-speed casting, and curved mould geometries. Modern steel shops are constantly striving to achieve extended SEN service life and improved operations. Consequently, the design, material selection, and manufacturing processes of SENs are crucial to meeting these performance goals. This paper presents recent developments in SEN technology, focusing on material recipe advancements and design optimisation using modelling techniques.

Introduction

In flat steel production, both thin and medium-thickness slab casting technologies have proven effective in meeting the industry's demands for high throughput, cost efficiency, and consistent steel quality. Thin slab casting, first implemented by SMS Group at Nucor Crawfordsville (USA) in 1989, remains operational and relevant in 2025. This process typically employs funnel-shaped moulds with thicknesses ranging from 50 to 110 mm and supports casting speeds of up to 5 tonnes per minute per strand. Over the decades, this technology has matured, enabling the production of increasingly complex steel grades [1,2]. The 30-year evolution and future outlook of this process have been comprehensively reviewed in the literature [3].

More recently, medium-thickness slab casting has gained traction as a viable alternative. These systems utilise moulds with thicknesses between 135 and 160 mm and can achieve casting rates of 8 to 10 tonnes per minute. Unlike thin slab casters, they typically feature parallel mould walls rather than a funnel design. This configuration helps reduce the risk of excessive turbulence at higher casting speeds and facilitates the integration of tube changers, thereby enhancing operational flexibility.

The transfer of molten steel from the tundish to the mould is managed by submerged entry nozzles (SENs), which are engineered to accommodate the specific flow dynamics of thin and medium-thickness slab casting. In thin slab applications, the SEN geometry transitions from a round inlet to a flattened outlet, often flaring outward to maintain flow capacity. This results in the widely adopted "beaver tail" design, which is complex to manufacture due to its intricate shape and tight tolerances. These nozzles play a critical role in controlling mould flow behaviour, minimising turbulence, and maintaining steel cleanliness. The influence of the SEN on steel quality and the various considerations for the design of these SENs are discussed in several articles [4,5]. Additionally, the design must ensure high resistance to slag corrosion and robust mechanical integrity. This article explores the engineering challenges and solutions involved in developing high-performance SENs for modern slab casting operations.

Materials Selection and Development

When the SEN becomes the limiting factor in casting sequence length, it is typically due to localised wear at the slag line caused by chemical corrosion. This degradation progressively thins the refractory wall, eventually reaching a point where continued operation poses a safety risk. If casting is not halted, the wall may breach, allowing molten steel to escape through the eroded section—potentially leading to severe operational hazards such as mould breakouts.

Inadequate protection against high-temperature exposure—whether during preheating or active casting—can also accelerate SEN degradation. Oxidation under these conditions further compromises the refractory material, increasing its susceptibility to corrosion. Representative examples of SEN failures resulting from these mechanisms are illustrated in Figure 1.

SENs are typically composed of three primary material zones, each engineered to meet specific operational demands:

- Body material: This forms the bulk of the SEN and is generally composed of an alumina-graphite composite.
- Slag band region: Located at the steel-slag interface, this zone requires enhanced corrosion resistance and is commonly made from zirconia-graphite materials.
- Seat area: This region interfaces with the stopper rod and must maintain dimensional stability and mechanical integrity during flow shut-off.

To address common failure mechanisms—such as slag line corrosion, oxidation, and thermal shock—RHI Magnesita initiated a targeted development programme focused on material innovation and design optimisation for thin slab SENs. The following sections outline the specific advancements made in each material region.

Body material

A specialised alumina-graphite formulation was engineered specifically for thin slab casting applications. The composition was refined regarding the refractory oxide content. For example, conventional brown fused alumina was substituted with higher-purity white fused alumina. This adjustment enhanced corrosion resistance and thermal stability. Additionally, the formulation was optimised to minimise thermal expansion hysteresis between heating and cooling cycles, thereby reducing the risk of crack formation due to thermal cycling.

Slag band material

For long-sequence casting operations, RHI Magnesita developed a new slag band composition. Key considerations included:

- Elimination of antioxidants: The revised formulation excludes antioxidants traditionally used in slag band recipes.
- Use of high-purity flake graphite: This enhances thermal conductivity and structural integrity.
- Zirconia phase optimisation: Unlike previous RHI Magnesita grades that utilised monoclinic zirconia, the new formulation incorporates only calcia-stabilised zirconia, improving phase stability under thermal and chemical stress.

Figure 1.

Examples of wear on SENs at the end of a 15-hour casting sequence: (a) hole-out and (b) "worm holes" on the refractory surface.

(a) (b)

Details of the developments can also be found in a previously reported study [6]. These changes significantly improved slag resistance, as confirmed by both laboratory testing and operational trials. Figure 2 illustrates the surface condition of the new slag band material after a casting sequence at a thin slab caster. Mould flux penetration was limited to approximately 1.5 mm, with zirconia grain degradation confined to this outer layer. The underlying material remained structurally intact.

Importantly, thermal expansion compatibility between the slag band and body materials was also addressed. By aligning their thermal expansion behaviours, internal stresses during heating are minimised, enhancing the SEN's resistance to thermal shock and reducing the likelihood of crack propagation.

Oxidation protection

Removal of antioxidants from the refractory composition, while beneficial for corrosion resistance, introduces a higher susceptibility to oxidation, particularly when the surface is exposed to elevated temperatures in the presence of oxygen. Without appropriate countermeasures, this can lead to premature surface degradation and reduced service life.

To address this challenge, RHI Magnesita developed a new surface glaze formulation designed to act as a protective barrier against oxidation. This glaze layer significantly enhances the refractory's resistance to high-temperature oxidative environments, preserving surface integrity throughout preheating and casting operations. The effectiveness of this protective layer is demonstrated in Figure 3, which shows a SEN surface post-casting with minimal signs of oxidation-related damage.

Designs and Development of Manufacturing Techniques

As previously outlined, the geometry of thin slab SENs is highly complex, presenting significant challenges in manufacturing. The isostatic pressing process used to form these components requires intricate and high-precision tooling. These tooling systems are not only technically demanding but also represent a substantial capital investment, often amounting to tens of thousands of dollars. Moreover, the design complexity and sensitivity of the materials can lead to elevated scrap rates, driven by both process variability and material inconsistencies.

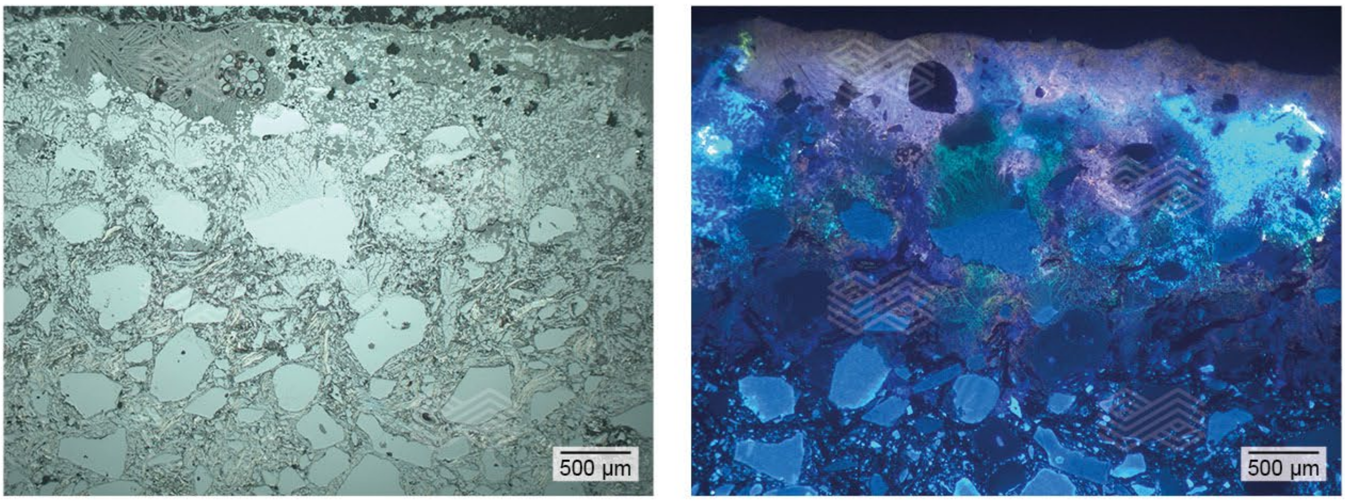
Figure 3.

Examples of the refractory surface protected by the improved glaze: (a) cut section showing minimal signs of oxidation-related damage and (b) external view.

(a) (b)

Figure 2.

Photomicrographs of the newly developed zirconia-graphite slag band material after casting: (a) optical and (b) cathodoluminescence microscopy showing that mould flux penetration was limited to approximately 1.5 mm and zirconia grain degradation was confined to this outer layer.



(a) (b)

To address these issues, RHI Magnesita developed and implemented a novel manufacturing technology specifically tailored for thin slab SEN production. This innovation has led to a marked improvement in manufacturing efficiency, reducing both tooling-related costs and scrap rates, while maintaining the high dimensional accuracy and material integrity required for reliable SEN performance.

Development and Evaluation of Thin Slab Designs

SENs are essential components in continuous casting, responsible for directing molten steel from the tundish into the mould while maintaining flow stability and minimising casting defects [7]. Their role becomes even more critical in thin slab casting, where high casting speeds and narrow mould cross-sections demand precise flow control to ensure product quality [8].

Achieving stable, symmetric flow patterns within the mould is a key objective, as these conditions help reduce surface defects and internal inclusions. SEN design features that influence flow behaviour can be effectively analysed and optimised using physical and computational modelling techniques. Examples of visualisations using these two techniques are shown in Figure 4.

Most thin and medium-thickness slab SENs begin with a circular bore at the inlet, which transitions into a geometry that narrows in one direction while flaring outward in the other. This gradual transformation is crucial to prevent flow separation from the nozzle walls, which could otherwise introduce turbulence and instability into the mould.

At the nozzle exit, a central divider is typically incorporated to split the flow into two distinct streams. These streams are discharged through dual ports, which may also include internal baffles. The configuration of these dividers and baffles plays a pivotal role in controlling the steel flow distribution—specifically, the proportion directed upwards toward the meniscus versus downwards into the mould cavity. These flow dynamics are critical for maintaining optimal mould heat transfer and minimising surface turbulence. Some of these details can be observed in Figure 5.

Figure 5.
Image showing flow separation (blue box) in the SEN bore.

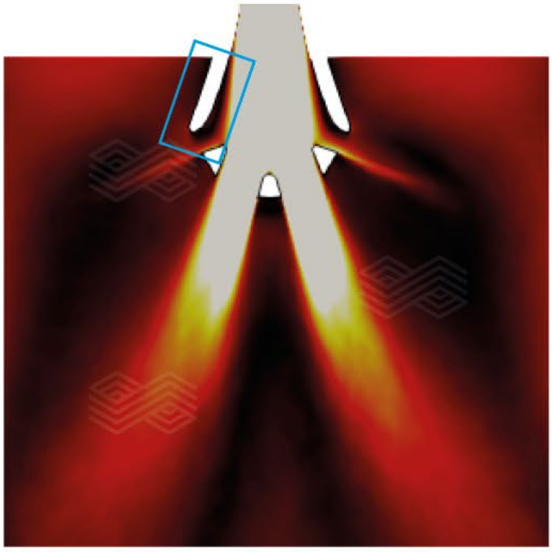
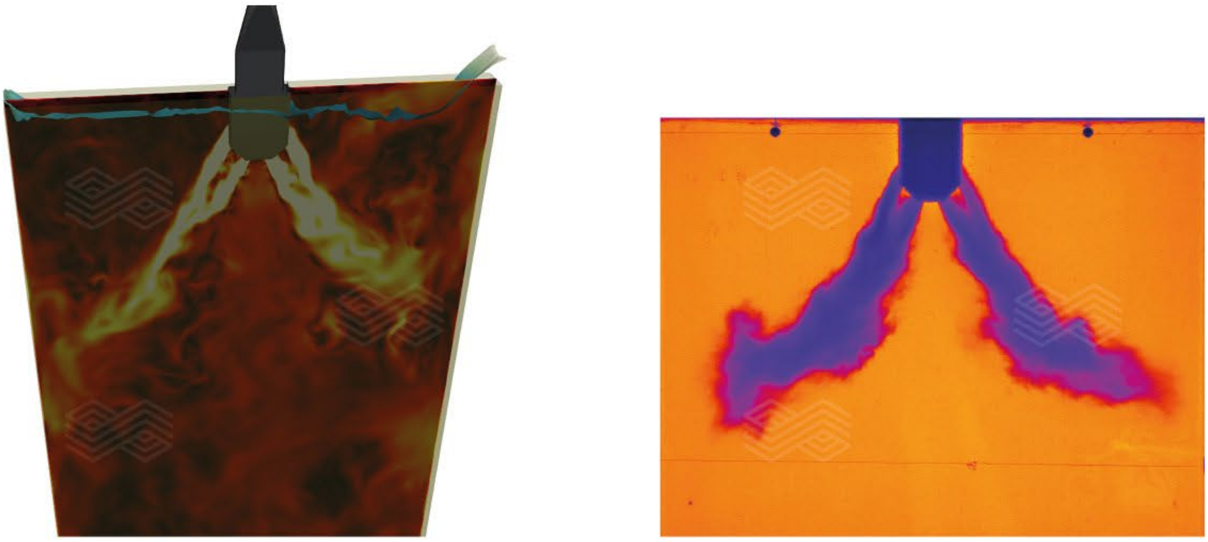


Figure 4.
Molten steel flow evaluation in the mould using (a) computational and (b) water modelling techniques.



(a) (b)

Thermomechanical analysis

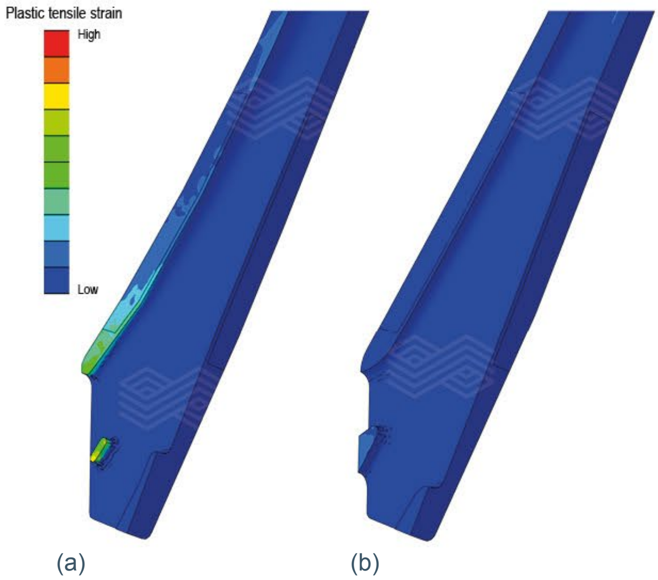
SENs and associated refractory components are subjected to extreme thermal environments during both preheating and casting operations. The selection of refractory materials and the geometric design of these components must account for not only peak temperatures but also transient thermal gradients, particularly during intermediate phases such as the off-gas period between preheating and casting.

To gain a detailed understanding of the thermal behaviour during preheating, a prototype SEN was instrumented with thermocouples at strategic locations. Data collected during these trials revealed temperatures reaching up to 1400 °C. Multiple test iterations confirmed the repeatability of these thermal profiles. The temperature profiles and additional details are presented in a separate technical article [9].

Design features and material choices significantly influence the structural integrity of the SEN under operational conditions. For instance, internal elements such as flow dividers and baffles, if inadequately designed, can introduce stress concentrations that may lead to premature failure due to thermal and mechanical loading. Finite element analysis (FEA) was employed to evaluate the thermomechanical performance of various SEN configurations. These simulations incorporated realistic thermal boundary conditions representative of the casting process stages: Rapid heating during preheating, thermal soak, cooling during the off-gas phase, and differential exposure during casting, where the SEN bore and submerged exterior are in contact with molten steel, while the upper section remains exposed to ambient conditions.

Figure 6.

FEA-simulated plastic tensile strain for two different SEN designs: (a) Design 1, featuring a narrower baffle and divider, exhibited higher tensile strain and (b) Design 2 showed lower tensile strain.

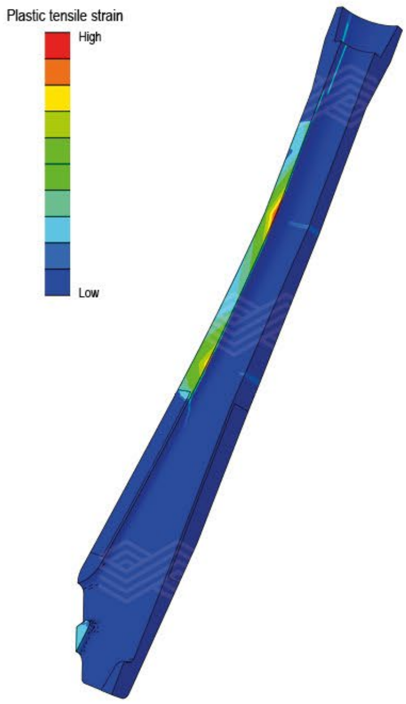


The resulting thermal gradients induce mechanical stresses, strains, and plastic strains which were quantified using coupled thermal and mechanical simulations. Figure 6 presents a representative FEA result, showing the distribution of plastic tensile strain across a symmetric quarter of the SEN geometry. Under identical thermal conditions, Design 1, featuring a narrower baffle and divider, exhibited elevated strain levels compared to the more robust Design 2.

Stress and hence strain distributions vary across different casting stages. As shown in Figure 7, during casting, elevated plastic strain was observed along the narrow face of the SEN, particularly near transitions in geometry and material interfaces. These findings underscore the importance of material compatibility and the need for smooth geometric transitions to mitigate stress concentrations and enhance component longevity.

Figure 7.

FEA-simulation showing higher plastic strain observed near material and geometry interfaces of the SEN.



Flow analysis

As previously noted, the internal flow characteristics governed by the geometric configuration of the SEN are critical to achieving optimal steel quality during continuous casting. Several studies have explored the impact of specific design features and proposed optimisation strategies to enhance flow control [10]. However, the effectiveness of any SEN design is highly dependent on the mould geometry and casting parameters.

To ensure relevance and accuracy, design evaluations must be conducted under the specific operational conditions in which the SEN will be deployed. For several results reported in this study, simulations were performed for mould widths of approximately 1460 mm, with casting speeds ranging from 2 to 3 tonnes per minute. Time-dependent CFD simulations were utilised to analyse transient flow behaviour and assess the performance of various SEN configurations under these representative conditions. A representative geometry of the SEN is shown in Figure 8.

Figure 9 illustrates the instantaneous velocity distribution within the mould, captured in a vertical plane along the mould's broad face at the mid-thickness section. The velocity contours and vector fields reveal a time-dependent yet highly stable and repeatable flow pattern. Two distinct flow streams are observed symmetrically on either side of the mould centreline. The jets exiting the upper ports are directed toward the narrow faces, where they rise toward the meniscus before recirculating downward along the SEN's outer surface. Simultaneously, the lower ports emit downward-directed jets that converge into a single stream beneath the SEN.

This configuration results in a classic double-roll flow structure. The upper roll is formed by streams turning upwards near the narrow faces, while the lower roll develops beneath the SEN, driven by the interaction between the downward jets and the lateral flow toward the mould walls. This dual circulation pattern is critical for promoting uniform temperature distribution and minimising inclusion entrapment during casting.

At higher casting rates, the overall flow structure within the mould remains qualitatively consistent with that observed at lower rates, though the velocity magnitudes increase proportionally. The fundamental flow topology exhibits minimal variation, indicating stable and repeatable behaviour across operating conditions.

A widely used parameter for assessing mould flow dynamics is the sub-meniscus velocity at the quarter-point location, defined as the midpoint between the SEN and the narrow face of the mould. Maintaining velocities within the range of 0.1 to 0.5 m/s at these points is generally considered optimal for promoting uniform surface flow and minimising defects.

Figure 8.

Representative geometry of the thin slab SEN used in the steel flow simulations.

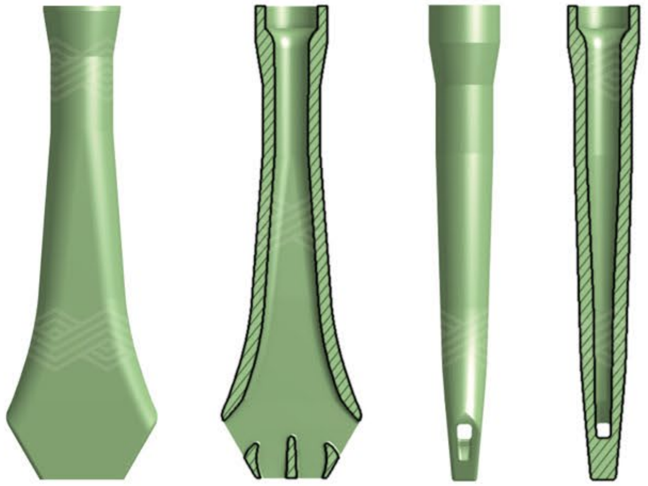
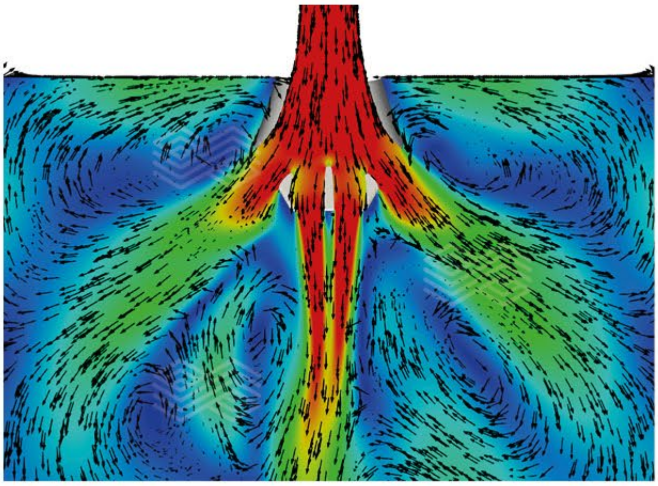


Figure 9.

CFD simulation showing the instantaneous velocity distribution on a broadside midplane in the mould.



For the SEN configuration evaluated in this study, velocity profiles at the quarter-point monitor locations were recorded during the simulations for casting speeds of 2.2 tonnes/minute and 2.9 tonnes/minute. These results, presented in Figure 10, include data from both the left and right monitoring positions relative to the SEN, illustrating the symmetry and consistency of the flow field under varying throughput conditions.

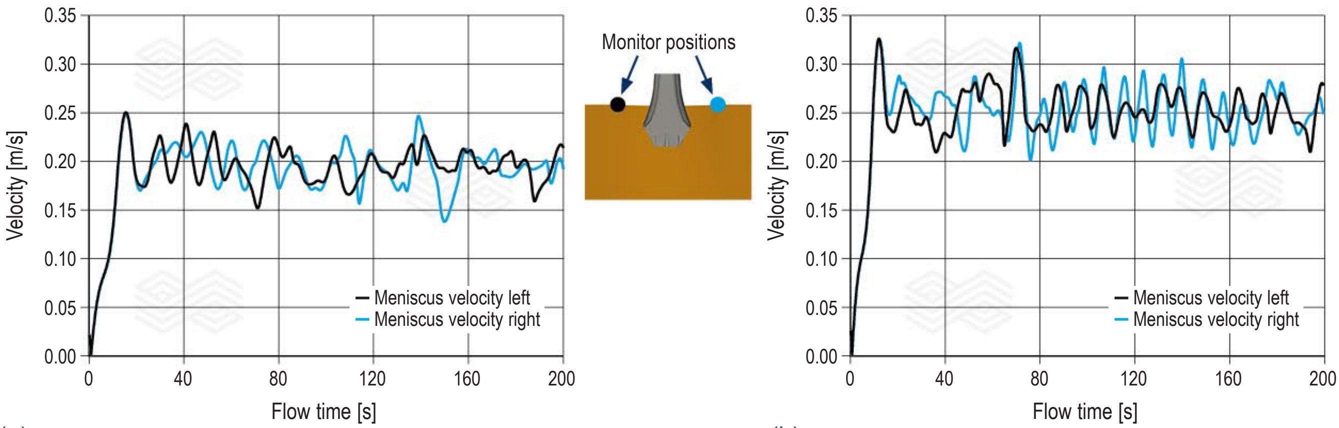
The expected meniscus surface wave height is estimated from the simulated flow parameters. Figure 11a shows the plot of values calculated over time and in Figure 11b these wave height values are averaged over time.

Key observations from the sub-meniscus velocity and surface behaviour can be summarised as follows:

- Temporal stability: While sub-meniscus velocities exhibited temporal fluctuations, these variations remained confined within a narrow band, indicating a stable flow regime.
- Casting rate-dependent magnitude: As anticipated, the mean velocity increased with higher casting throughput, consistent with the elevated volumetric flow rate.
- Operational range compliance: In both casting scenarios, the velocities consistently fell within the favourable operational window of 0.1–0.5 m/s, supporting effective mould flow control.
- Symmetry and phase alignment: Velocity profiles at the left and right quarter-point monitor locations were nearly identical in magnitude and phase. This symmetry confirmed the absence of lateral flow bias and reinforced the overall stability of the mould flow field.
- Meniscus activity: Estimated wave heights at the meniscus suggested a dynamic yet controlled surface condition—active enough to promote surface renewal without inducing excessive turbulence.
- Surface uniformity: The close agreement in time-averaged wave heights between the left and right sides of the mould further validated the uniformity of flow and surface behaviour across the mould width.

Figure 10.

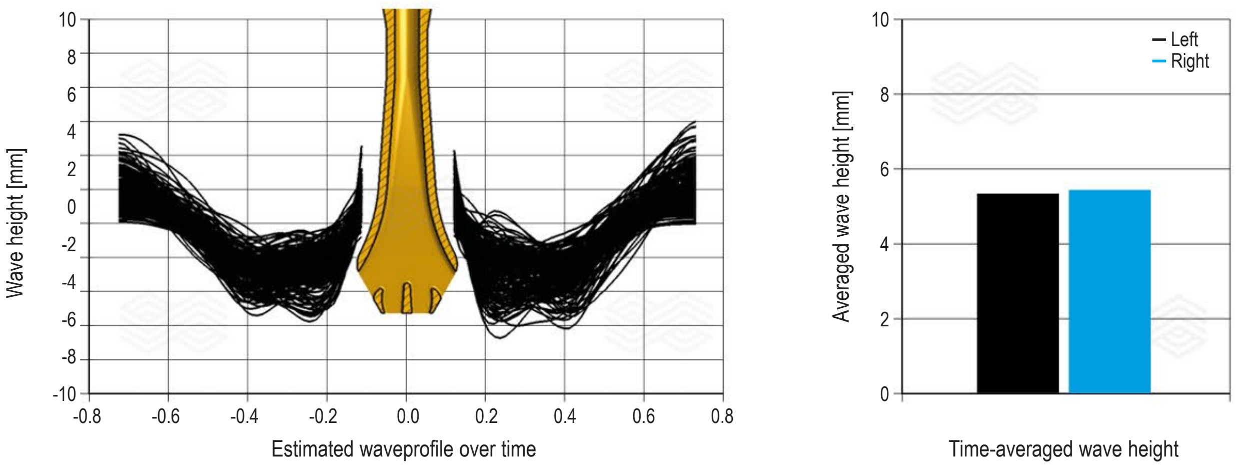
Simulated velocity plots at sub-meniscus quarter-width left and right monitoring positions for two casting rates: (a) 2.2 tonnes/minute and (b) 2.9 tonnes/minute.



(a) (b)

Figure 11.

(a) estimated wave heights at the meniscus over time and (b) time-averaged wave height from simulations.



(a) (b)

SEN Designs for Medium-Thickness Slab Casters

As previously outlined, medium-thickness slab casters offer several operational advantages, including the use of parallel mould configurations that help reduce mould turbulence and the capability to support higher casting throughputs. However, these benefits also introduce unique challenges, particularly for SEN design, due to the broad range of mould widths typically accommodated by such casters (e.g., 900 mm to 2600 mm).

Designing SENs that perform reliably across this wide operational envelope requires careful consideration of flow dynamics, thermal behaviour, and structural integrity. Despite the variability in mould dimensions and casting rates, the fundamental methodology for evaluating SEN designs remains consistent with the approach previously described, leveraging modelling, thermal-mechanical analysis, and flow diagnostics to ensure robust performance across all operating conditions.

Figure 12 presents velocity contour snapshots and meniscus surface fluctuation profiles derived from CFD simulations of 3 different SEN configurations. The presented results include:

- Designs 1 and 2: Applied to casting dimensions of 1950 mm × 130 mm at a throughput of 7.5 tonnes/minute.
- Design 3: Applied to casting dimensions of 2100 mm × 130 mm at a throughput of 8.1 tonnes/minute.

These simulations were conducted under conditions representative of medium-thickness slab casting with parallel mould configurations operating at high throughput. Additionally, dye injection results from physical water modelling for Design 2 are shown in Figure 13. The qualitative agreement between the two methods confirms the reliability of the CFD predictions in capturing key flow behaviours within this casting setup. Additional details of the modelling and results can be found in a published study [11].

SEN Changer for Medium-Thickness Slab Casters

In standard slab casting, with a mould thickness of 200 mm or more, tube changing is relatively common. In medium-thickness slab casting, typically around 135 mm in thickness, designing a SEN that accommodates a wide casting width range (900 mm to 2600 mm) presents significant challenges, particularly when a SEN changer system is employed. The width of the SEN dictates the minimum casting width necessary to allow for a tube change. At higher casting

Figure 12.

Velocity contour snapshots and meniscus surface fluctuation profiles derived from CFD simulations of medium-thick casting with (a) Design 1, (b) Design 2, and (c) Design 3.

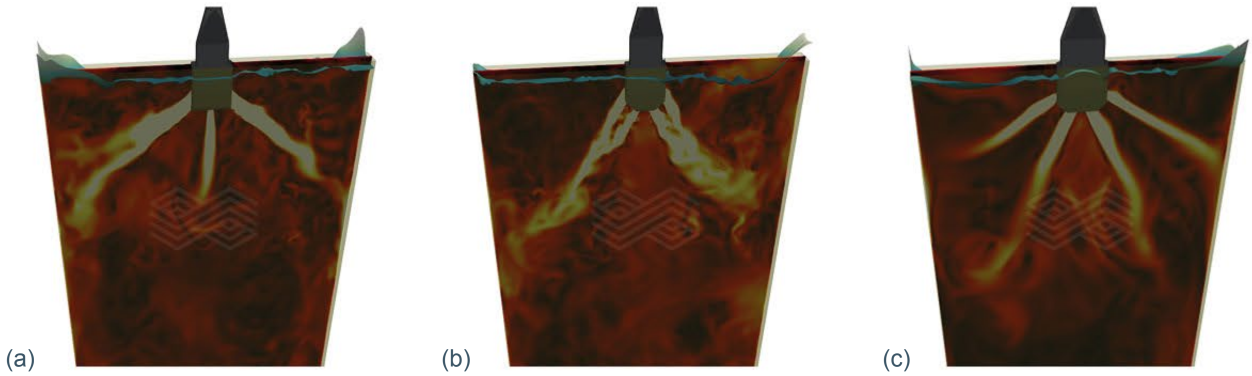
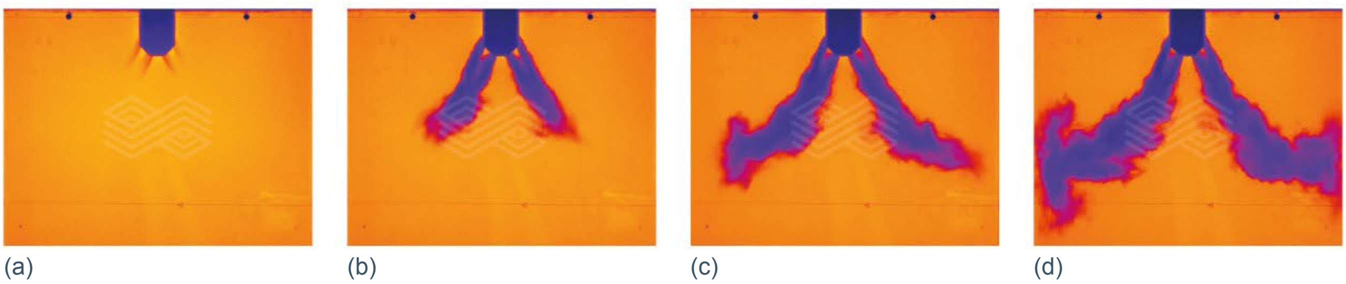


Figure 13.

Physical water modelling of medium-thickness slab casting with Design 2. Images (a)–(d) were taken at time intervals of 0.33 seconds after the start of dye injection.



throughputs, increasing the nozzle width effectively reduces flow turbulence but raises the minimum castable width. This relationship and the mechanism of a tube change is illustrated in Figure 14. In this example, a SEN width of 250 mm limits the minimum allowable mould width to 1000 mm.

To address this trade-off, a hybrid nozzle geometry has been adopted: The upper bore diameter is maintained at approximately 100 mm to support SEN changer compatibility, while the lower section features a flat profile with a width between 200 mm and 300 mm. This configuration balances flow stability with the mechanical constraints of the changer system, enabling smoother transitions across a broad range of casting widths.

Beyond nozzle geometry, additional operational challenges include preventing tundish lifting and dynamically adjusting casting speeds during SEN changes. In response, RHI Magnesita has developed a specialised SEN changer system tailored for these applications. This system incorporates an integrated safety plate, eliminating the need for blind plate handling and enhancing operational safety. Ongoing development efforts continue to focus on optimising this SEN changer system to ensure cost-effective, reliable performance in high-throughput, medium-thickness slab casting environments. This SEN changer is also capable of being operated with an automatic robot or manipulator, further enhancing operational safety.

Field Implementation

Following thermomechanical simulations, fluid flow analyses, and internal material testing, the newly developed SENs were deployed for field trials at thin slab casters in North America. The implementation of these optimised designs and materials, combined with strong operational and ramping practices by the caster team, resulted in a significant improvement in SEN service life.

While previously limited to approximately 12–14 hours of service life at thin slab casters, the new SENs—featuring improved materials and designs—have routinely enabled casting sequences exceeding 30 hours. One notable example includes a 34-hour casting sequence involving predominantly high-carbon grades, where the SEN retained approximately 10 mm of refractory thickness at its most eroded point (Figure 15). In another case, the SEN was pushed to the operational limits of the caster, completing

Figure 14.

Schematic showing the SEN change in a mould and the minimum width required.

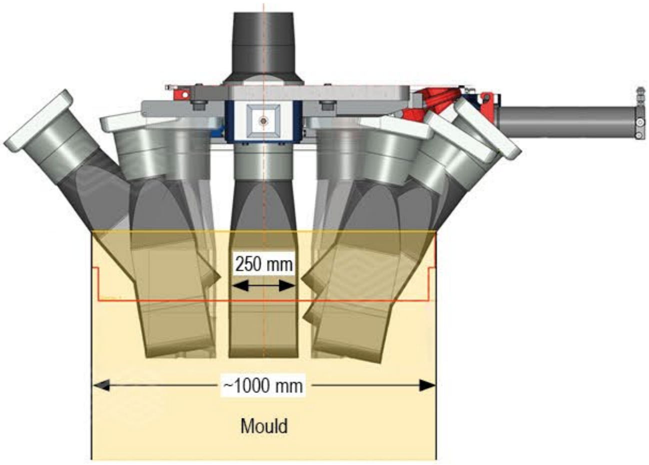


Figure 15.

The newly developed SEN after a 34-hour casting sequence with predominantly high-carbon steel grades: (a) external view of the slag band region and (b) cut section though the slag band showing the SEN retained approximately 10 mm of refractory thickness at its most eroded point.


(a)


(b)

40 heats of medium-carbon steel over 34.5 hours and delivering more than 5000 tonnes of steel (Figure 16).

Summary

Thin and medium-thickness casters continue to push the boundaries of productivity through increased casting speeds, high throughputs, and extended sequence lengths. These advancements place significant performance demands on the SEN, necessitating robust design and material solutions. RHI Magnesita undertook a comprehensive evaluation of SEN performance parameters, leveraging material science, manufacturing processes, and computational modelling. This multi-faceted approach led to the development of the TS SEN series, engineered to meet the rigorous demands of modern thin slab casting operations. Where previous SENs were typically limited to lifespans of approximately 15 hours, the newly developed TS SENs have demonstrated consistent performance in casting sequences exceeding 30 hours. Medium-thickness casters pose a different, yet similar challenge. By leveraging similar tools and techniques, functionally superior SENs are being designed and evaluated for these applications as well.

Figure 16.

Example of a new SEN after 34.5 hours casting medium carbon grades: (a) lower section, (b) exterior surface of slag band, and (c) thinnest section on slag band.

(a) (b) (c)

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Bulletin

The Journal of Refractory Innovations

2025

Published by RHI Magnesita GmbH, Vienna, Austria
Chief Editor Thomas Prietl
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