A PATHWAY TO OPTIMIZE NOZZLE DESIGN AND METAL FLOW STABILITY IN CONTINUOUS CASTING PROCESSES

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Abstract

Real-time measurements in steel continuous casting are challenging due to extreme temperatures, leading to limited process understanding and frequent breakouts. This project aims to address this issue of casting process control by simulating steel flow using a low-melting-point Bi-Sn alloy with steel-like properties, enabling real-time analysis of pressure, velocity, vibrations, and mold level fluctuations to optimize stopper-nozzle designs. A novel glass window in the nozzle rod provides unprecedented visibility into liquid metal flow under varying inert gas injection rates. Results from Swerim's unique Continuous Casting Simulator (CCS), the world's only facility of its kind, are validated through SSAB plant trials. This innovation drives greater efficiency, fewer breakouts, and a deeper understanding of casting dynamics, marking a transformative leap for the steel industry.

Keywords: Continuous casting, liquid metal, nozzle, steel, under-pressure

1. INTRODUCTION

Steel is a cornerstone of modern industrial development, serving as a critical material in diverse applications ranging from skyscrapers and transportation systems to household appliances. Its versatility and mechanical properties make it indispensable across industries. However, the production of steel is a complex process that varies significantly depending on the intended application. Over the decades, advancements in steel manufacturing techniques have led to the widespread adoption of Continuous Casting (CC), a process in which molten steel is solidified into semi-finished strands in a continuous manner [1]. The stability of this process and the quality of the final product are influenced by numerous factors, including the physical dimensions of the casting mould, the quality of raw materials, and the flow dynamics of molten steel during casting [2]. Among these, flow regulation is particularly critical, as it directly impacts the homogeneity and integrity of the cast steel. In the CC process, stopper systems are commonly employed to control the flow of molten steel from the tundish to the mould, especially for high-grade steel production. However, the flow regulation region is prone to severe under-pressures and pressure fluctuations, particularly near the stopper tip and the narrowest gap. These conditions can lead to operational challenges such as air infiltration through refractory materials, undesirable flow patterns, and even cavitation. Such issues can result in defects like inclusions and mould level instabilities, which compromise product quality and increase the risk of breakouts [3]. To mitigate these risks, real-time monitoring of flow velocity, pressure distribution, and vibrational behavior is essential. However, the extreme temperatures required to maintain steel in its molten state (approximately 1,500℃) create a highly challenging environment for direct measurement and analysis [4]. This limitation complicates efforts to optimize flow dynamics and enhance casting quality.

To address these challenges, researchers often employ analogous materials that mimic the flow characteristics of molten steel but can be studied at lower temperatures. One such material is the eutectic bismuth-tin alloy (Bi 58%-Sn 42%), which has a melting point of 135℃ [5]. This alloy exhibits thermal, electrical, and viscous properties that closely resemble those of molten steel, making it an ideal candidate for simulating CC processes under more manageable conditions [6]. By using this alloy, researchers can conduct detailed investigations into flow behavior, pressure distribution, and system stability without the constraints imposed by the extreme temperatures of molten steel.

This study focuses on analyzing the pressure distribution in the vicinity of the stopper and Submerged Entry Nozzle (SEN) throat within a Continuous Casting Simulator (CCS) present at Swerim. In addition to pressure measurements, the study examines the liquid metal flow through the nozzle rod with respect to variation in argon gas injection rate via glass window. The primary objective is to deepen the understanding of how flow regulation influences pressure dynamics in the CC process, with the goal of identifying potential risks and improving both process efficiency and product quality. The findings from the technical-scale CCS experiments conducted at Swerim are cross-referenced with data from an industrial caster at SSAB Luleå. This comparative approach ensures the relevance and applicability of the results to real-world industrial operations.

2. MATERIALS AND METHODS

2.1 Continuous Casting Simulator

The CCS features a tundish equipped with an adjustable stopper to regulate the flow of liquid metal. The molten material flows from the tundish through a tundish pipe and a SEN into the mold. The mold, designed with dimensions scaled to replicate industrial flow conditions, comprises a main chamber connected to a secondary chamber via an opening at the bottom. The liquid is recirculated from the secondary chamber back to the tundish, creating a closed-loop system. Most flow measurements are conducted within the mold. A key distinction between the CCS and real-world continuous casting is the absence of solidification in the simulator. **Figure 1** provides a schematic overview of the CCS, while **Table 1** details its specifications.

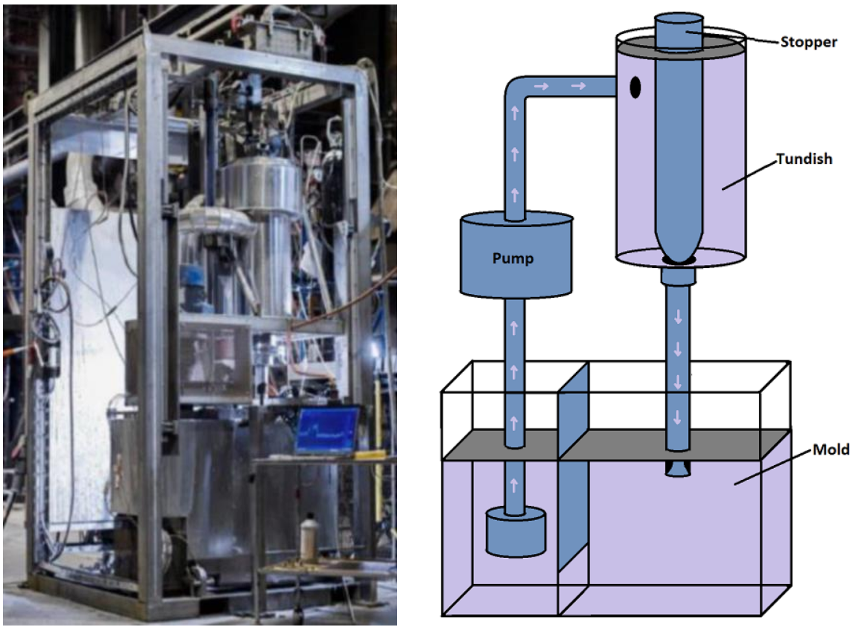

Figure 1 Continuous Casting Simulator at Swerim

Table 1 Specifications of the Continuous Casting simulator

Mold size	0.92 depth x 0.22 width x 1.2 length (m)	Fixed
Cating Speed	0.6 – 1 (m/min)	Changed according to flow
Argon flow rate	<7 (liters/min)	Changed according to flow
Stopper position	0.01 – 0.017 (m)	Changed according to flow
Tundish level	0.8 – 0.9 (m)	Inferred from level sensor
Immersion depth	0.6 or 0.7 (m)	Submersion depth of SEN to mold

2.2 Glass window installation

The CCS design facilitates seamless testing of various stopper-nozzle configurations, thanks to its user-friendly mounting system for the stopper and nozzle rod. This allows refractory components to be evaluated with minimal machining requirements. In this study, the nozzle-tip is cast in aluminum and integrated effortlessly into the nozzle rod. Furthermore, to check whether the liquid metal sticks to the transparent glass thereby making them opaque/burn the glass, two different set-ups of lab-scale tests were carried out.

- *Static liquid metal trials*: Four different kinds of test tube coatings were explored in such a way that the test tubes were dipped in the liquid metal for ~7 hours at 170℃
- *Dynamic liquid metal trials*: Test tubes coated in various additives were dipped in a centrifuging ring with the liquid metal in it, facilitating a flow similar to CCS.

After testing the quartz glass test tubes in a much-controlled lab environment, possibilities for procuring quartz glass window were being considered. **Figure 2** illustrates the straightforward assembly of the aluminum nozzle into the nozzle rod, as well as the installation of the glass window for observation of liquid metal flow. The construction made used of an O-ring and screws facilitating an easy removal of glass window in case of glass scattering or to re-apply additives.

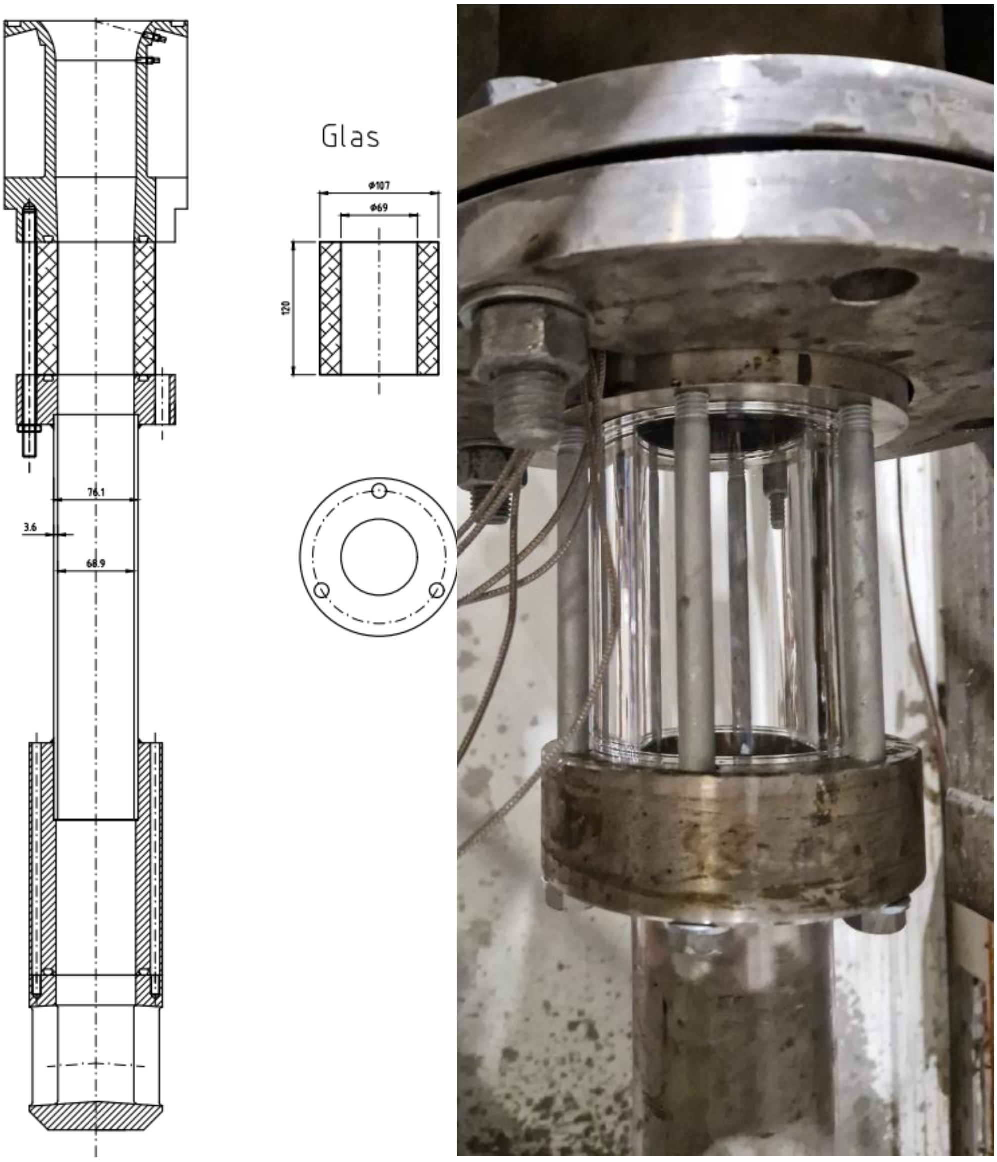

Figure 2 Schematic of nozzle rod, and pictorial representation of glass window installed in the CCS facility

2.3 Technical scale trials

Technical scale trials with CCS at Swerim is being carried out with varying casting speed and argon injection rate, which was capable of measuring stopper lift, argon line pressure, vibrations, pressure developed along the stopper tip-nozzle crown, and mould level fluctuations. Having a good grasp of these data will in turn result in prediction of under-pressure conditions, suggesting the best nozzle-stopper combination. The best combination will be tested in industrial environment at SSAB at a later stage.

3. RESULTS

3.1 Installation of glass window

Before the actual purchase of quartz glass window, lab-scale tests were done to check whether the glass window works in Swerim's CCS environment, it was crucial to test the transparent glass tube in the liquid metal at an operating temperature of 170℃ for at least 7 hours. Hence, static and dynamic lab-scale tests were carried out for quartz test tubes with the following type of additives, as shown in T**able 2**:

Table 2 Quartz test tubes with the following type of coating/additives

Test tube number	Test tube coating
1	Waterglass coated
2	Teflon coated
3	Standard quartz test tube
4	Oil coated

- Static liquid metal trials: Four different kinds of test tube coatings were explored in such a way that the test tubes were dipped in the liquid metal for ~7 hours at 170℃. From **Figure 3**, it can be inferred that the test tube 4, with oil coating appeared clean even after 7 hours of dipping in the liquid metal, in a static environment.

Figure 3 Test tube numbers 1 to 4, starting from left to right

- Dynamic liquid metal trials: Test tubes coated in various additives were dipped in an annular flow rotating ring with the liquid metal in it, facilitating a flow similar to CCS. It was observed that the quartz test tube with oil coating outperformed every other combination in this test as well. Hence, oil coating on the procured glass window was planned to try-out.

From the trials, it was observed that the glass window worked with oil coating. Although, illumination near the glass window to clearly observe the flow is to be considered from next trials onwards. It was noted that the glass window almost turned opaque (indicating purely liquid metal flow without any argon gas injection) during under-pressure conditions. **Figure 4** depicts the glass window during and after the trials indicating that the glass window can be re-used again by re-applying oil for the next trials.

Figure 4 Glass window during (left) and after (right) the trials

3.2 Technical scale trials

Technical scale trials in CCS at Swerim predicted the stopper lift, argon line pressure, vibrations, pressure developed along the stopper tip-nozzle crown, and mold level fluctuations. This gave rise to the nozzle-stopper combination that produces under-pressure and positive pressure. Six different combinations of different types of stopper-nozzle combinations were tried out at various casting speed and argon injection rate, hence the 6 cases in **Figure 5**. It can be ascertained that the cases 1, 2, and 3 depicts positive pressure whereas cases 4, 5, and 6 depicts under-pressure at lower argon injection rate confirming the vulnerability of cavitation. Cases 1 and 4 were tested at SSAB in an industrial caster environment, where it was confirmed that the under-pressure is prominent in case 4 whereas it is possible to overcome the issue of under-pressure (at same casting conditions) just by changing the stopper-nozzle combination to case-1.

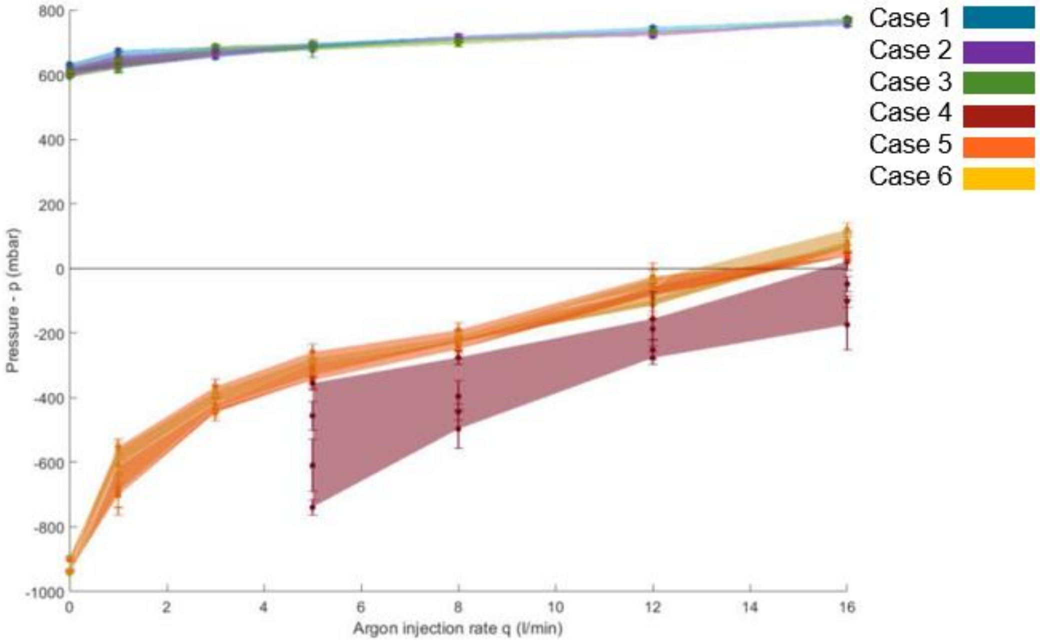

Figure 5 Pressure variation in the argon line with respect to change in argon injection rate at 1 m/min casting speed

4. CONCLUSION

Successful completion of the work lead to the following conclusions:

- A glass window coated with oil has been shown to be the most effective method for observing the gas-liquid behavior of argon and metal flow in the flow regulation region during the continuous casting process.
- Testing various stopper-nozzle combinations gave the concept of under-pressure and what design to avoid while designing stopper and nozzle.
- The under-pressure scenario (case 4) and the optimum pressure scenario (case 1) was checked at SSAB at an industrial scale, proving that under-pressure developed during case 1. This further strengthens the credibility of CCS data.

As a continuation, further cases will be tested at SSAB along with an intention to upscale the mold size of CCS present at Swerim, with more sensors leading to more casting data.

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