AI-Driven Temperature Control in Secondary Metallurgy Based on Continuous Temperature Measurement

Digital technologies are transforming industry at all levels. Steel has the opportunity to lead all heavy industries as an early adopter of specific digital technologies to improve our sustainability and competitiveness. This column is part of AIST's strategy to become the epicenter for steel's digital transformation, by providing a variety of platforms to showcase and disseminate Industry 4.0 knowledge specific for steel manufacturing, from big-picture concepts to specific processes.

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Introduction

Steelmaking, Sustainability and Digitalization

The steelmaking industry has experienced notable developments and encountered various challenges in recent years. One significant development is the increasing emphasis on low-carbon steelmaking, driven by the need to reduce carbon emissions. This transition has resulted in a greater reliance on electricity, leading to higher energy costs for steel producers. Additionally, the industry is grappling with the issue of excess capacity, with projections indicating a potential resurgence of the steel crisis witnessed in 2014. In response to these challenges, sustainability has emerged as a key priority, with efforts focused on reducing the environmental impact of steel production and exploring greener manufacturing processes. Furthermore, digitalization is revolutionizing the steelmaking sector, with the adoption of advanced technologies such as automation, data analytics and artificial intelligence. These digital advancements aim to enhance operational efficiency, improve productivity and enable better decision-making within the industry.

Türkiye holds a significant position in the global iron and steel production economy. According to the latest data from the World Steel Association (worldsteel) for the years 2012–2021, when examining countries' steel production and rankings, China emerges as the country with the highest steel production capacity worldwide. Türkiye, on the other hand, plays a crucial role in global steel production and is ranked seventh in the world (Fig. 1).[1]

One of the Biggest EAFs in the World: Çolakoğlu® Metalurji

Çolakoğlu is a diversified conglomerate in Türkiye involved in steel production, shipping, energy, information systems, mining, foreign trade and finance. Today the group employs 12,000 people and the company's involvement in the iron and steel business began in 1945.

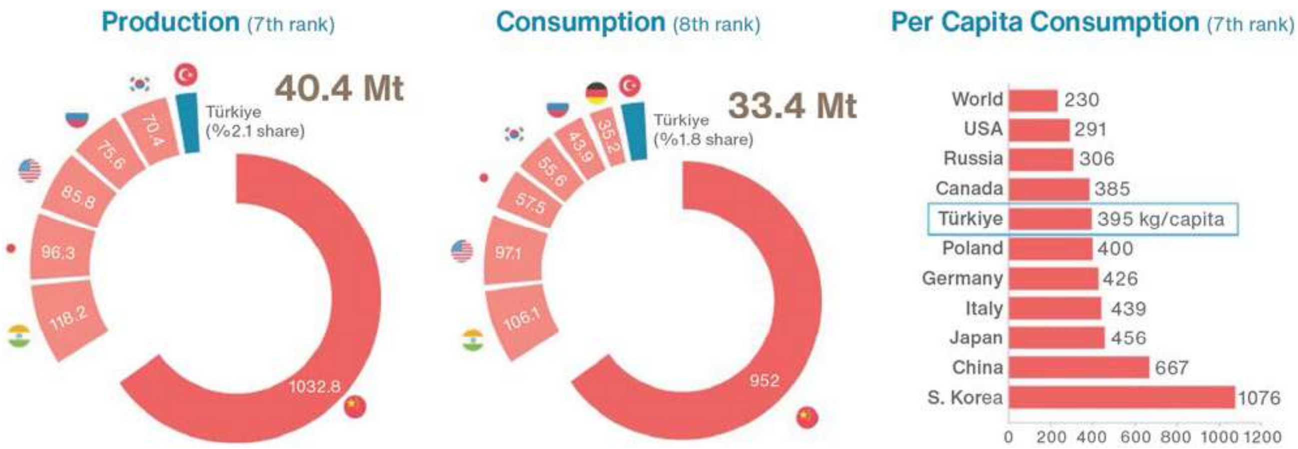
Equipped with one of the world's biggest electric arc furnaces (EAFs), Çolakoğlu Metalurji meltshop ranks among the world's most advanced crude steel production facilities today. The company's ladle furnaces are equipped with a magnetic stirrer and argon gas injection system that ensures homogeneity and hence the quality of the finished product. In addition, a twin-tank vacuum degasser improves steel quality through degasification in castings, a process that is especially critical in flat product manufacturing.

Motivation of Project

Due to the increasing demands in steel production and consumption

Figure 1

Crude steel production and consumption of countries with the per capita consumptions.



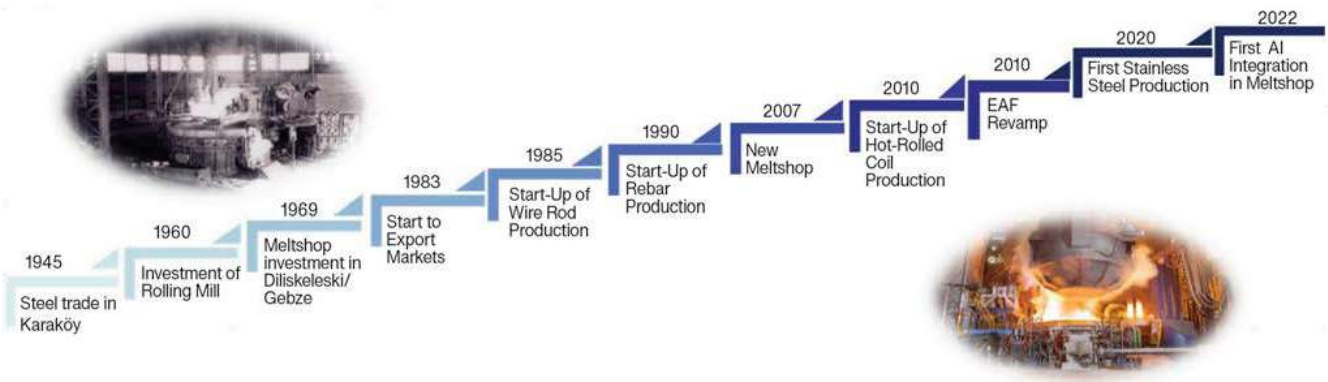
processes in today's technology, consecutive process and new product development studies have been initiated in Türkiye and worldwide. Sustainability and digitalization have become the most popular agendas in recent years, particularly in the realm of green steel production, where steel producers engage in discussions and undertake development efforts on various platforms. With its technological infrastructure, Çolakoğlu Metalurji maintains the title of being the steel production facility with the lowest environmental emissions in Türkiye. Pursuing a policy of continuous improvement, numerous projects have been initiated, especially aiming at reducing production and energy-related emissions. Reduction of superheat in the steel production process, leading to energy savings, is a primary focus of these initiatives. The goal is to achieve energy savings that will result in a reduction in scope 2 emissions. In line with all these objectives, artificial intelligence technology, which is independent of human input and more robust, has been utilized as an assistant in decision-making during the production process. The integrated model processes data obtained from level 1, 2 and 3 systems, and through learning, it suggests the most accurate temperature information, with a critical input being the measurement and increased data frequency of liquid steel temperature within the tundish. This continuous temperature measurement system, CasTemp, has been incorporated into the process.

Smart Steel Technologies: Revolutionizing the Core of Steel Production

Smart Steel Technologies (SST) supports steel manufacturers by providing AI-based software systems for production planning and process optimization. SST Temperature AI is a production-ready solution for optimized temperature control that unlocks the following energy- and cost-saving potentials in the meltshop:

Figure 2

Historical evolution of Çolakoğlu Metalurji.



- Increase in process stability and safety: SST Temperature AI employs high-resolution data and advanced AI algorithms to foresee temperature changes of a heat throughout its entire process chain, leading to a reduction of uncertainty and, therefore, of temperature variances. In particular, this also reduces the number of cold heats and route deviations, two highly unwanted phenomena that severely impact steel plant logistics.
- Reduction in energy consumption, materials and emissions: The aforementioned increase in process stability reduces the need for temperature buffers, leading to a notable decline in energy usage and CO_2 emissions. Less uncertainty in primary steelmaking propagates all the way to secondary metallurgy, leading to savings, e.g., in the usage of cooling scrap and aluminum.
- Leveraging digitalization in steelmaking through data-driven insights: The AI technology benefits from the guidance of domain experts, ensuring the development of a robust and reliable process.

Figure 3

CasTemp SH dashboard and liquidus measurement sensors.

CasTemp Superheat System

The continuous and reliable measurement of liquid steel temperature, a critical process parameter during mold casting of liquid steel, significantly influences the casting process and the final product quality. At Heraeus Electro-Nite, the development and sustainable utilization of the CasTemp system, enabling dynamic temperature control in continuous casting processes, along with the integrated liquidus measurement and superheat control system (CasTip), have become a primary focus. Heraeus Electro-Nite facilitates the continuous measurement of liquid steel temperature in the continuous casting process and enables superheat control through the developed liquidus measurement sensor.

The CasTip system performs liquidus measurement by using a submersible probe to extract a liquid steel sample into its chamber, and through specialized sensors, it measures the thermal solidification temperature via the phase diagram. The system works in conjunction with the CasTemp system and employs the measured critical temperature, determined by the company, to create a model after the liquidus measurement. Utilizing this model, the system proactively alerts the operator to prevent tundish cooling. Furthermore, by ensuring accurate liquidus measurement and continuous temperature monitoring, the system effectively manages ladle furnace outlet temperatures, enabling operation within the desired critical temperature range and providing the capability for controlled operation at maximum speed.[2]

Practical Site Studies

SST Temperature AI in the Meltshop of Çolakoğlu Metalurji

In the meltshop at Çolakoğlu Metalurji, the intricate and expansive production process, featuring multiple stations and on-demand steel production, poses a complex challenge when it comes to optimizing temperature control for individual heats. SST Temperature AI was first deployed at the plant in mid-2022 and has been continuously fine-tuned ever since. The following models of SST Temperature AI are integrated at Çolakoğlu Metalurji:

- SST LF Exit Temperature Recommendation: Recommends the optimal exit temperature at the ladle furnace to achieve a desired aim temperature in the tundish. It supports cases where the LF is succeeded by other processes such as vacuum degassing.
- SST SecMet Exit Temperature Recommendation: Recommends the optimal exit temperature at the final station of the secondary metallurgy to achieve a desired aim temperature in the tundish.
- SST Tundish End Temperature Prediction: Predicts the tundish temperature of a heat at the end of its cast.
- SST EAF Total Energy Recommendation: Recommends the optimal, total specific electrical energy at the EAF to achieve a desired aim temperature at certain downstream stations.

The models of SST Temperature AI are customized specifically for the meltshop of Çolakoğlu Metalurji: Its specific process routes (all of which are supported), its equipment and its produced steel grades. The algorithms learn from historical data, utilizing all relevant L1 and L2 signals that influence the steel temperature. These signals include:

- Station-specific parameters: Temperature measurements, chemical analyses, additions, relevant time series signals, and ladle transport and treatment times.
- Ladle properties: Times the ladle was empty and full, ladle age, ladle wall temperatures, ladle preheating, ladle tare weight and steel weight.
- Caster: Position of the heat in the tundish, casting speeds and throughput.
- Steel chemistry: Actual and aim analyses.

Moreover, the models do not only take into account the signals of the heat under consideration, i.e., the heat for which it wants to make predictions or give recommendations, it also looks at surrounding heats, particularly past heats. This is illustrated by Fig. 4.

Fig. 4 highlights a typical heat H6 in ladle L1 while it is treated in the ladle furnace. In the running casting sequence, the heats H1 in ladle L1, H2 in L2, and H3 in L3 have already been cast. At the time of the prediction, heat H4 in ladle L4 is being cast, while heat H5 in ladle L5 is on its way from the ladle furnace to the continuous caster. For the calculation of temperature predictions and recommendations for heat H6, SST considers all relevant heats mentioned above and their parameters.

Strategies of SST Temperature AI for Reduced Energy Consumption

SST Temperature AI uses machine learning algorithms that outperform conventional approaches such as simplified, manually crafted formulas and averages, deterministic rule-based models, as well as classical mathematical-physical models. Fig. 5 shows how SST Temperature AI optimizes temperature control at each point in the meltshop.

In a first step, temperature fluctuations are reduced, decreasing the uncertainty about the steel temperature. This removes the need for unnecessarily big temperature buffers. Thus, in a second step, the overall temperature level may be decreased in order to reduce energy consumption while at the same time retaining process stability.

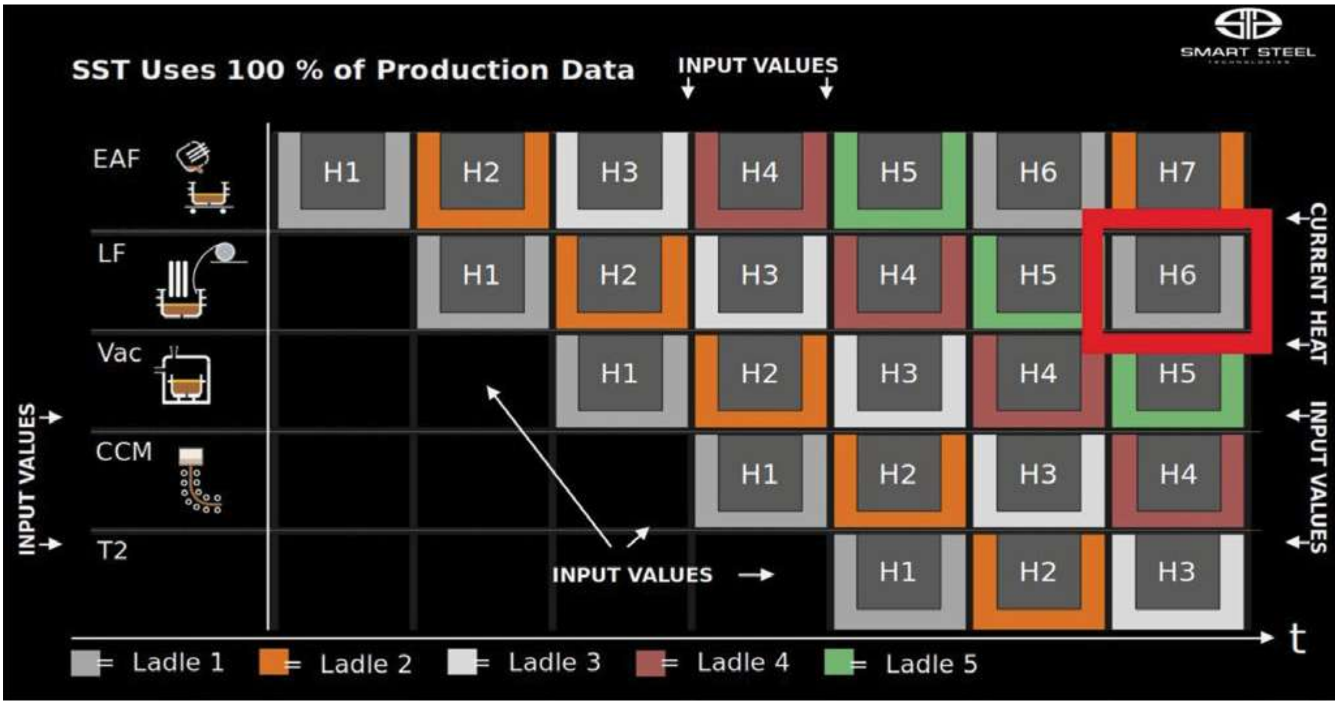
Setup and Approach of the Analysis

This study will compare production parameters from three different time periods:

- Period 1: Before the use of SST Temperature AI.
    - This period consists of the first 3 months of the project, after SST's data replication had been set up, but before the models of SST

Figure 4

Principle of typical heat cycles at different stations in different ladles.



Temperature AI had been integrated into the production process of Çolakoğlu Metalurji.

- Period 2: With SST Temperature AI, but before CasTemp.
  - This period consists of the final 3 months before the introduction of CasTemp. At this point, the SST Temperature AI models had reached a high level of maturity, and they were extensively used by Çolakoğlu Metalurji.
- Period 3: With SST Temperature AI and with CasTemp.
  - This period consists of the first 3 months after the introduction of CasTemp.

In order to study the reduction in energy consumption in a meltshop featuring an electric arc furnace and two ladle furnaces, one may assume that the best way to do so lies in the analysis of the total electrical energy consumed per ton of steel. However, this proves to be difficult for the following reasons: First, energy consumption depends on the distribution of energy input between the electric arc furnace and the ladle furnace, and this distribution may change over time. Second, scrap quality is subject to availability and may thus fluctuate over time. Third, different weather conditions, most notably temperature, precipitation and humidity, influence the energy needed to melt the scrap in the electric arc furnace.

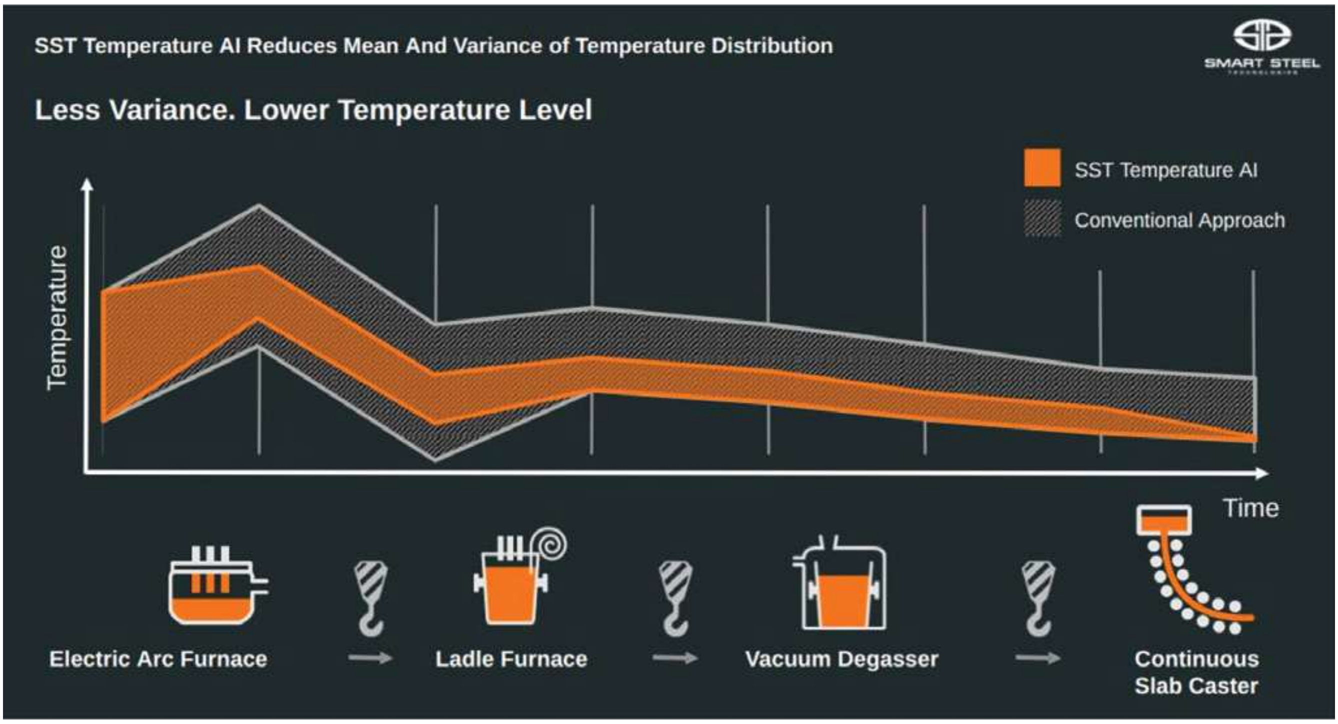
This study, therefore, builds its approach on top of temperature measurements. However, the tundish temperature measurements must be part of the metrics used, since Period 3 saw the introduction of CasTemp and thus, in particular, of a new tundish temperature measurement system. This introduction also led to a difference in the amount and distribution of dip measurements in the tundish. In short, it is not reasonable to devise a metric based on tundish temperature measurements if the three periods are not comparable with respect to them. One is thus left with the temperature measurements from the secondary metallurgy. Since Çolakoğlu Metalurji produces a vast array of high-quality steel grades, the metric has to take into account the different chemical properties of each steel grade. One such property is the liquidus temperature based on the aim chemical composition of the steel grade. However, only considering different liquidus temperatures would not do justice to the complexity of the problem, since different steel grades are also cast at different aim superheats. Thus, the metric M is defined as follows:

$$M = \text{actual secmet exit temperature} - \text{aim tundish temperature}$$

where aim tundish temperature = aim liquidus temperature + aim superheat in the tundish.

Figure 5

Impact of SST Temperature AI in the meltshop.



Here the common abbreviation "secmet" is used for secondary metallurgy. Since aim superheats are subject to change across longer time periods, they were fixed in time for the analysis and the same aim values were used per steel grade. In other words, a given steel grade will have the same representative aim superheat in the analysis of all of the above three periods, even if a specific heat with that steel grade produced in Period 1 may have actually had a slightly different aim superheat than another heat with the same steel grade produced in Period 2. Moreover, when talking about exit temperatures, the authors excluded such heats from the analysis that had experienced additional electrical heating after the final temperature measurement at the given station, since for these heats one can only estimate at which temperature they actually left the station.

The integration of SST Temperature AI in the meltshop of Çolakoğlu Metalurji has demonstrably yielded a significant reduction of the overall temperature level by 17%. To be more precise, the weighted average of the per-route decrease of the above metric M (and thus of the global temperature level) between Period 1 and Period 2 is equal to 17%.

Dip Temp and CasTemp Comparison Figures — VUI's With CasTemp System

After implementation of the CasTemp SH system, the comparison of manual dip temperature measurements and continuous measurements were performed. As it can be seen clearly in Fig. 5, although through the casting period the average temperature values between dip temperatures and CasTemp are parallel, the fluctuations of values can be increased.

The red curve represents dip temperature traces and blue curve represents continuous temps. Due to external factors including operator competency, tundish cover and flux, and hardware issues in temperature lances, measured values can fluctuate tremendously. When the blue curve is analyzed it is clearly noticed that consistency of measured data was greater. One of the most important input parameters for the LF Exit Recommendation model is updated measured steel temperature in the tundish. When the measured temperature values do not represent real conditions or, in other words, when they are not consistent with each other, the predictive power of the model will decrease.

The CasTemp sensor was positioned in the vicinity that is closest to the strand to mitigate the influence of external factors. Upon analyzing a single tundish sequence, a notable correlation between CasTemp readings and manually recorded dips is evident (see Fig. 6). Nevertheless, the precision and consistency of temperature measurements for accurate control necessitate careful attention to data frequency. In Fig. 7, a detailed examination of temperature traces is presented. Although both measurements coincided at 02:20, the manual temperature readings indicate a relatively stable steel temperature in the tundish for approximately 40 minutes. In contrast, the steel temperature, as per CasTemp, exhibited a noteworthy decrease of around 12°C during the same period, signifying a substantial change.

Temperature Reductions Via SST SecMet Exit Model and CasTemp System

As stated earlier, the installation of the CasTemp SH System has enhanced precision in tundish temperature control, providing the model with a greater opportunity for improvement. With continuous measurements offering more frequent temperature readings, the model can now update itself more frequently and adapt to changes with heightened precision. Furthermore, continuous measurement has a substantial impact on data stability and has the ability to address certain edge cases to a significant extent. Further to the advancements outlined above, the integration of the CasTemp SH System has notably augmented the precision of tundish temperature control,

Figure 6

Graphical comparison of manual and continuous temperature measurement.

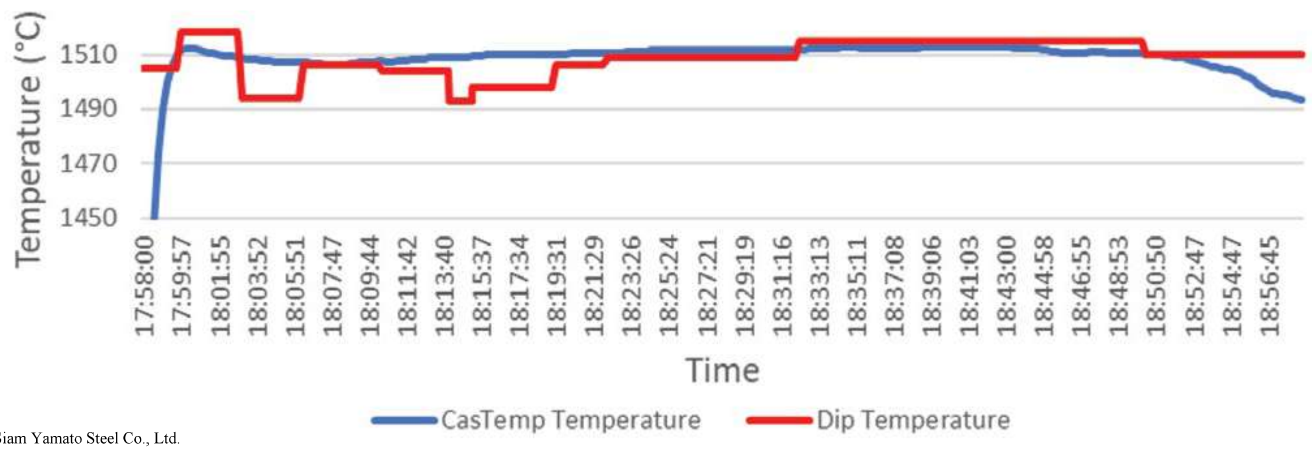
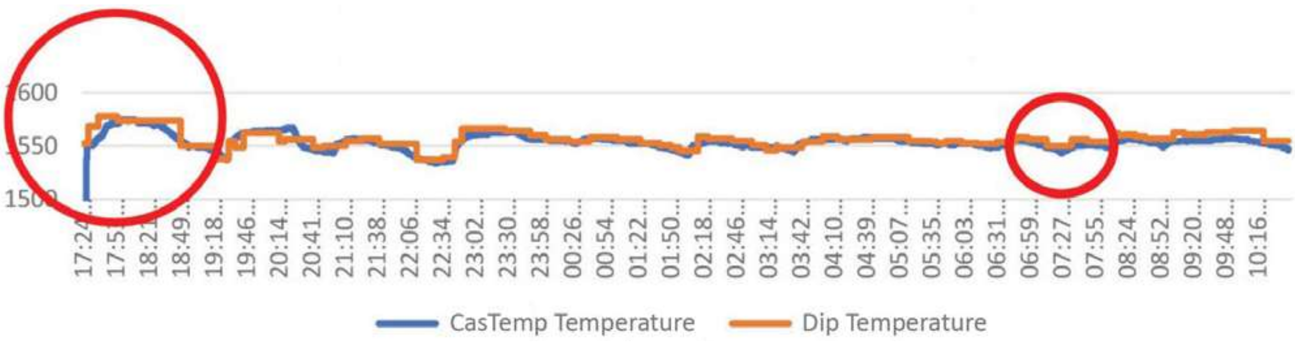


Figure 7

Temperature trends of both continuous and manual measurement through one sequence.



thereby furnishing the model with an expanded scope for refinement. The installation of CasTemp SH System at the meltshop of Çolakoğlu Metalurji alongside SST Temperature AI has led to another substantial decrease of the overall temperature level by 2.4%. To be more precise, the weighted average of the per-route decrease of the above metric M (and thus of the global temperature level) between Period 2 and Period 3 is equal to 2.4%. The integration of the CasTemp SH System has notably increased tundish temperature control, which opened up the possibility of further decreasing the temperature level.

Conclusions

Safety

Using existing technologies, the liquid steel temperature within the tundish is periodically measured by operators through the utilization of disposable thermocouples based on the immersion temperature measurement principle. The measurement duration, dependent on the response time of the thermocouple, lasts between 4 to 6 seconds. During this period, the operator must maintain the measurement lance in close proximity to the liquid steel without moving it. In facilities with integrated CasTemp systems, a refractory-coated sensor is placed within a crucible integrated into the tundish body, allowing for long lasting temperature measurement within the tundish. This product, installed by the refractory team, enables the measurement of liquid steel temperature throughout a service cycle of the tundish.

In today's technology-driven steel production facilities, achieving zero workplace accidents is paramount. In this context, ongoing measures are taken across all processes to leverage evolving technology. Heraeus Electro-Nite contributes to accident prevention through the development of unattended and dynamic measurement and control systems for steel production and continuous casting processes, mitigating potential incidents associated with conventional measurement techniques. Table 1 summarizes the periodic occupational health and safety advantages offered by advanced temperature measurement systems utilized in continuous casting processes.

Figure 8

Detailed trace analysis of CasTemp and manual measurements.

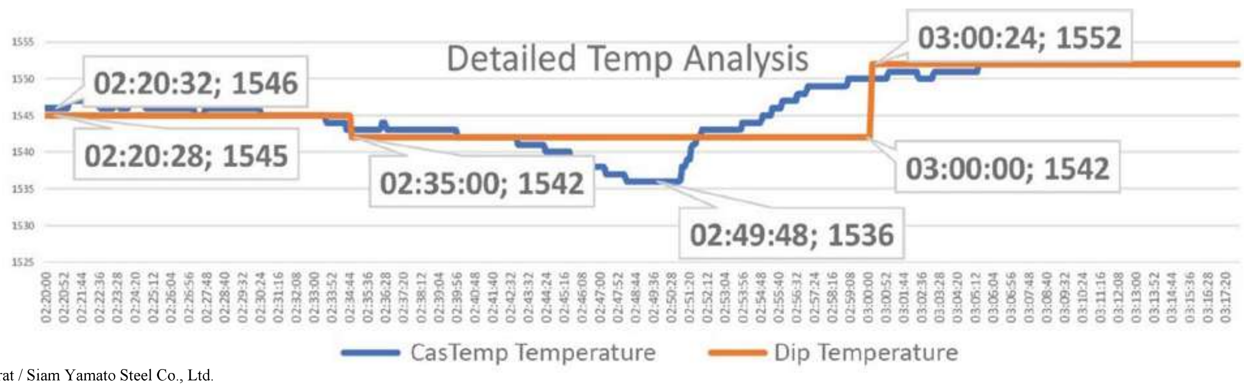


Table 1

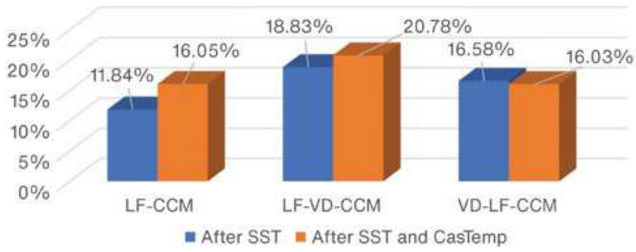
Continuous Temperature Measurement System Health, Safety and Environmental Advantage Matrix for CasTemp SH

Parameters	Case 1	Case 2	Case 3
Tundish sequence	20	40	80
Dip measurement (count)	60	120	240
Temperature measurement time (seconds)	600	1,200	2,400
Temperature measurement time (minutes/day)	10	20	40
Temperature measurement time (minutes/month)	300	600	1,200
Temperature measurement time (minutes/year)	3,600	7,200	14,400
Temperature measurement time (hours/year)	60	120	240
Working hour (labor * measurement time)	600	1,200	2,400
Accident frequency rate (accidents/year)	0.0192	0.0384	0.0768

Measurement time was calculated as 10 seconds. Labor working at plant assumed as 10. Accident frequency rate was calculated as 32/1,000,000 working hour.

Figure 9

Reduction of difference between secondary metallurgy exit and tundish aim temperatures.



Energy and CO_2 Emission Reduction

Following the successful integration of SST and CasTemp systems, a noteworthy reduction in superheat (SH) within secondary metallurgy units has been achieved. As illustrated in Fig. 9, the average SH reduction for along the whole route amounted to 17%, facilitated by the implementation of the SST SecMet Exit Model. The introduction of continuous temperature monitoring through the CasTemp system significantly enhanced data acquisition, escalating the frequency from six temperature readings per ladle to 180 temperature data points. With this refined setup, an additional 2.4% reduction in superheat was realized.

Last but not least, substantial temperature reduction in secondary metallurgy enables to Çolakoğlu Metalurji not only energy saving but also lower process time, lower refractory consumption and eventually reduction of CO_2 emissions. It was clearly seen that Çolakoğlu Metalurji could manage to save 3,490 mWh of energy yearly and more than 1,745 tons of CO_2 emission will be decreased, which is comparable to taking around 6,500 short-haul flights (each covering 250 miles).

References

1. Istanbul Policy Center, https://ipc.sabanciuniv.edu/en/publications.
2. B. Hale, "Green Steel: Every Degree Counts," *AISTech 2023 Conference Proceedings,* 2023.

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