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Mapping, Educating, Training, Applying models in continuous CASTing

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1. INTRODUCTION

Continuous casting is a highly complex and dynamic process, so the use of numerical simulations has become essential for optimizing performance and ensuring product quality. For these models to be reliable, accurate validation with industrial data and lab-scale models is critical. Validation confirms that simulations reflect real process behavior, enabling confident decision-making in areas like process control and defect prevention.

We will present six case studies where success has been achieved in the optimization of industrial processes, reviewing the approaches and explaining their significance in industry by describing the process of validation, providing real-life cases where modelling has significantly improved the casting process in the steel industry.

2. CASE STUDIES

This section presents a few cases where modelling and validation of models has led to success stories relevant to industrial use and implementation. It covers four use cases [1] [2] [3] which have been presented at the Simulation Platform repository for METACAST [4], where a detailed description of the models, workflows, and in one case also the model code has been provided. These four cases show the successes that can be achieved by employing process models for the optimization and investigation of industrial processes as complex as continuous casting in modern steelmaking. The four use cases cover all the relevant aspects of casting modelling, namely: a) concerning internal quality, via inclusion removal in tundish; b) as in a) but considering the stirring action with argon and related 2-phase modelling; c) concerning productivity and yield, via facing intermixing issues; d) concerning general flow and solidification , with modelling functional to a digital twin.

Moreover, two ongoing projects are being presented as well, which deal with improving the reliability and quality of steel casting through the form of digital twins. In both of them, online process modelling, evaluation and state prediction aim at improving the product, by avoiding defect formation and process instabilities like slag entrainment in the mold.

2.1. Inclusion agglomeration and separation in continuous slab casting tundish

2.1.1. Aim and general scope of model

The paper [3] investigates how inclusion agglomeration and separation occur in the tundish during continuous slab casting, and how these phenomena can be predicted using advanced numerical simulation. Since steel cleanness is one of the key quality criteria in modern steel production, understanding and enhancing inclusion removal is essential.

The study focuses on the role of flow conditions, particle collisions, and agglomeration mechanisms in promoting the formation of larger inclusion clusters, which are more easily removed at the melt surface. Real-world experiments are highly expensive or sometimes impossible, so the authors developed a comprehensive computational modelling framework combining a 3D CFD flow model, a stochastic Lagrangian particle model, and a new collision–agglomeration model based on kinetic gas theory and turbulent interaction.

2.1.2. Validation

The authors validated their newly developed collision–agglomeration model using two independent data sources: controlled laboratory measurements from literature and plant measurements from an operational slab caster.

Laboratory validation compared numerical results with a turbulent mixing layer experiment and showed excellent agreement in predicted particle size distributions. Plant validation confirmed that the model correctly reproduces the changes from inlet to outlet in an operational tundish.

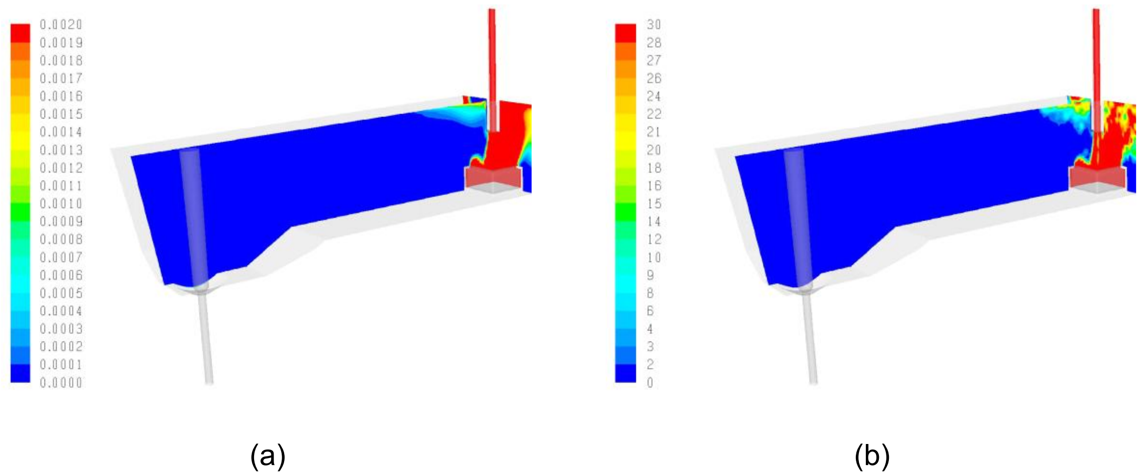


Figure 1. Numerical results for a tundish with small turbulence prevention pad, a) turbulent dissipation, b) number of inclusion collisions. [3]

2.1.3. Success in process optimization

The model was applied to investigate effects of casting conditions and flow control devices on inclusion behaviour. Findings indicated that turbulence prevention pads (TPPs) significantly enhance agglomeration by generating regions with high turbulent dissipation but low relative velocities. Agglomeration was shown to improve inclusion separation efficiency by up to 10%.

Casting rate showed minimal influence, while filling level and asymmetric shroud positioning had notable effects on agglomeration behaviour. The model also demonstrated that non-spherical inclusions agglomerate more readily.

Overall, the study provides a validated simulation approach capable of supporting tundish design and operational strategies to enhance steel cleanness.

2.2. Two-phase Flow Modelling of Argon Gas Injection in a Generic Tundish Using recurrence-CFD

2.2.1. Aim and general scope of model

The primary aim is to illustrate the applicability of rCFD—a reduced-order modelling technique that reconstructs long-duration flow evolution from previously computed CFD snapshots. The base case uses a DES-based CFD simulation with the mixture model to represent liquid steel and dispersed argon bubbles. This simulation captures key physical phenomena such as plume-driven recirculation, bubble dispersion, and turbulence enhancement. rCFD is then applied to this dataset to predict long-term flow behaviour without resolving the Navier–Stokes equations at each timestep.

This tutorial [4] presents a complete workflow for applying Recurrence Computational Fluid Dynamics (rCFD) to a two-phase argon injection tundish system, demonstrating how long-term unsteady multiphase flows can be simulated with a fraction of the computational cost of traditional CFD. The study uses a generic tundish geometry representing industrial continuous casting conditions and provides all necessary files (CFD case, rCFD scripts, UDFs, directory structure) for reproducing the methodology.

Two rCFD approaches are available: flow-based rCFD [5], which stores full flow fields (velocity, pressure, gas fraction) and stitches similar snapshots together, as well as transport-based rCFD, which uses cell-to-cell shifts to track scalar transport with greatly reduced memory requirements. In the provided example, flow-based rCFD has been implemented [2]. Available tutorials guide users through both Linux and Windows workflows using Scheme scripts that automate database preparation, recurrence matrix calculation, jump-path construction, and rCFD simulation execution.

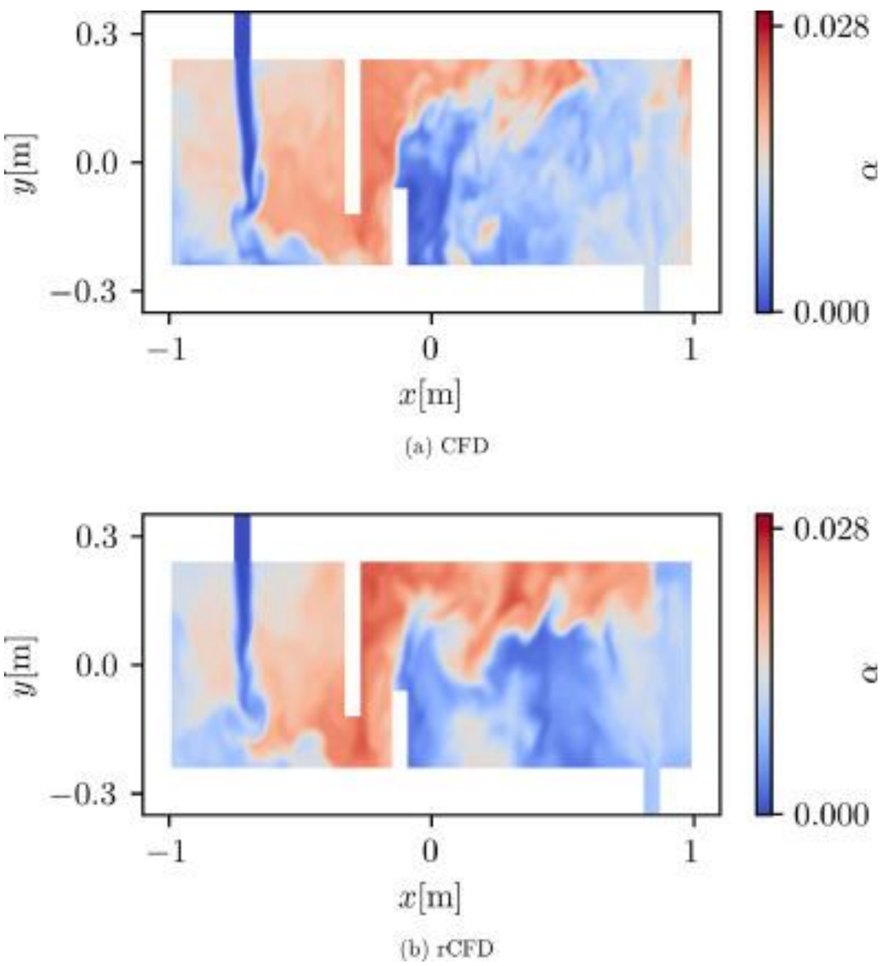


Figure 2. Species concentrations in the tundish. (a) CFD and (b) rCFD simulation results.

2.2.2. Validation

Validation occurs at two levels: validation of the CFD base case and validation of the recurrence concept.

The CFD base case assumes a DES turbulence model and structured mesh, which yield realistic representations of gas-induced unsteady flow in the tundish. Mixture velocity and gas-volume-fraction fields confirm proper recirculation and plume behaviour essential for recurrence analysis.

The recurrence matrix provides a visual confirmation of repeating flow states. Dark, diagonally aligned similarity bands demonstrate that the flow exhibits recurring patterns suitable for rCFD reconstruction. The recurrence path visualizations show how rCFD transitions between similar states over time, ensuring physically meaningful extrapolation.

Transport-based rCFD is further validated by geometry adjustments (inlet/outlet buffer volumes) that preserve mass conservation and boundary consistency.

Together, these validation elements demonstrate that rCFD reliably reproduces the dominant flow dynamics of the original CFD simulation.

2.2.3. Success in process optimization

The tutorial highlights rCFD's strength in performing long-duration simulations at dramatically reduced computational cost, enabling applications that would be impractical with fully transient CFD. This capability is crucial for metallurgical process optimization, where tasks such as residence-time distribution (RTD) studies, inclusion removal assessments, mixing efficiency evaluations, and parametric tuning of argon flow rates or tundish geometry require extended simulation horizons. The included case-specific UDFs and scripts demonstrate the practical execution of such studies using rCFD.

The workflow's robustness is enhanced through full automation of CFD–rCFD coupling, compatibility with multi-processor execution, and clear instructions for platform-dependent modifications (e.g., Windows command aliases, UDF compilation). The sample output video confirms that rCFD faithfully reproduces the essential bubble-driven flow structures seen in the original CFD data.

2.3. Online CFD- and Water-Model-Based Monitoring and Minimization of Steel Intermixing in Continuous Casting Tundish

This work [1] presents a validated, physics-based framework for predicting and minimizing steel grade intermixing during ladle changeover in a two-strand continuous casting tundish. Intermixing occurs when a new steel grade enters the tundish while the previous grade has not fully exited, creating transitional slabs with mixed chemistry that often require downgrading or scrapping. The proposed framework integrates Computational Fluid Dynamics (CFD), full scale water modelling, and analytical reactor theory into a practical monitoring and decision support system deployed both offline and online.

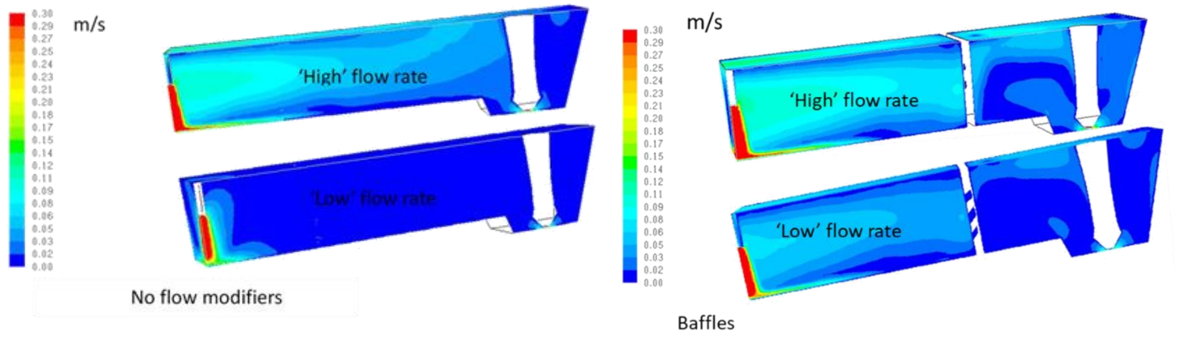
2.3.1. Aim and general scope of model

The primary aim is to develop a robust, generalizable, and industrially deployable modelling tool that predicts how alloy concentrations evolve at tundish outlets during grade transitions, enabling steelmakers to optimize cut plans, reduce downgraded length, and improve campaign scheduling.

The scope covers:

- Hydrodynamic characterization of the tundish, including velocity fields, dead zones, residence-time distributions (RTDs), and the effect of flow modifiers (no modifiers, impact pad, multi-hole baffle).
- Derivation of transition curves (C- and F-curves) from CFD data to describe the concentration evolution of chemical elements during intermixing.
- Analytical fitting of F-curves using exponential models with physically meaningful parameters (appearance time t_p, mean residence time t_{ave}, and mixing constant α). These fits enable fast predictions without rerunning CFD.
- Transformation of concentration-vs-time into concentration-vs-slab-length, allowing direct prediction of intermix slab lengths.
- Implementation into offline and online tools that support planner decision-making and real-time cut-control during casting.

Overall, the methodology serves as a bridge from fundamental fluid-flow physics to real operational optimization, with transferability to different tundish types and casting lines.



(a) (b)

Figure 3. Example of CFD results functional to the intermixing modelling tool development. (a) Velocity map (m/s) at surface and symmetry planes. No flow modifiers, (b) Velocity map (m/s) at surface and symmetry planes. Multiple hole baffles as flow modifiers.

2.3.2. Validation

A rigorous multi-stage validation was performed to compare the CFD with the water model.

Full-scale physical water modelling provided experimental measurements of first-appearance times and mixing behaviour. Agreement with CFD was strong across layouts, with different configurations for modifiers, impact pads as well as baffles. These results confirm that CFD accurately captures tundish behaviour and can reliably generate RTDs and transition curves.

Curve validation was also performed with analytical exponential fits applied to CFD-derived results. The comparison showed very small deviations, mostly confined to the earliest seconds of the transition. Parameters were stable and physically interpretable, demonstrating that the simplified model effectively reproduces full CFD behaviour.

Ultimately, also validation on plant scale was considered. Industrial validation included:

- Chemical sampling of slabs during real grade transitions, showing close alignment between measured and predicted chemistry evolution.
- Process-signal correlation, such as mould heat transfer variations occurring at the predicted concentration thresholds (e.g., 80% new grade).

- Successful application in asymmetric casting conditions, proving robustness even under non-ideal production states.

The validation on different scales confirms that the framework reliably predicts intermixing, both in controlled experimental settings and real industrial operation.

2.3.3. Success in process optimization

The implementation of the validated model in both offline and online environments has led to measurable improvements in operational efficiency and product quality: the reduction of intermixing length, the offline planning optimization, as well as a real-time online optimization.

Hydrodynamic insights revealed how flow modifiers influence mixing: no modifiers imply larger dead zones, short-circuiting, and longer intermix lengths. The impact of pads/ baffles is to generate a smoother, more uniform flow with reduced dead volume and shorter, more predictable transitions. These findings support layout optimization and better tundish design decisions.

The offline planner uses model-derived parameters to predict intermixing lengths for any combination of casting speed, tundish level, layout, and grade chemistry. Moreover, optimal cut positions are suggested to isolate mixed steel in minimal slab length. This allows for different scenario simulations for improved campaign planning, reducing scrap and supporting more flexible multi-grade sequencing.

The online tool integrates real-time plant data to continuously track intermix development during casting, recommend dynamic cut points based on current chemistry evolution, identify compatible grades for downstream transitions and respond adaptively to casting variations (speed changes, refill delays, asymmetric strand operation).

The key operational outcomes are:

- Significant reduction in downgraded tonnage due to accurate prediction and precise cutting.
- Enhanced yield and more stable production schedules.
- Fast computations thanks to analytical model structure, avoiding constant CFD runs.

- High transferability, requiring only minimal tuning when applied to different caster setups.

2.4. A digital twin framework for the simulation of fluid flow, heat transfer, and solidification phenomena in industrial continuous casting processes

2.4.1. Aim and general scope of model

Swerim's digital twin framework [6] for continuous casting provides an advanced, physics-based simulation environment designed to reproduce the key phenomena governing steel solidification inside the mould. Built on detailed CAD geometries supplied by industrial partners, the model incorporates real plant data on casting speeds, thermo-physical properties, cooling settings, and mould powder behaviour. Its primary objective is to offer steelmakers a reliable virtual platform for evaluating casting performance, troubleshooting operational issues, and optimising process conditions without costly full-scale trials.

A digital twin framework for the simulation of fluid flow, heat transfer, and solidification phenomena in industrial continuous casting processes

The digital twin integrates multiphase turbulent flow, heat transfer, solidification, slag infiltration, and mould oscillation in a fully transient 3D environment. Free surface behaviour between steel, slag, and air is captured using the Volume of Fluid (VoF) method, while solidification is modelled through an enthalpy–porosity approach that naturally represents mushy zone behavior. Turbulence is modelled using k–ε, RSM, or Large Eddy Simulation, depending on the need for fidelity near submerged entry nozzles or slag–metal interfaces.

A distinguishing capability of the system is its explicit representation of slag layers, including liquid flow, melting, drainage into the mould–strand gap, and the formation of solid slag films. This avoids simplifying assumptions commonly used in traditional casting models. The framework further incorporates temperature dependent material behaviour, electromagnetic stirring (EMS), mould oscillation, and thermo-mechanical interactions affecting shell growth and lubrication.

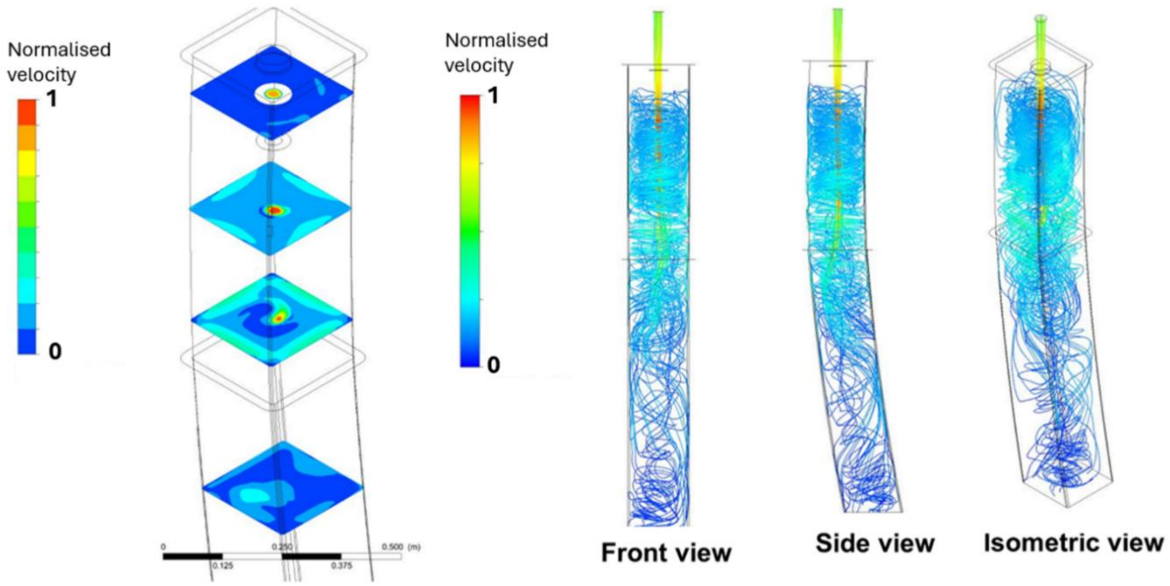


Figure 4. Sidenor's velocity plane and flow pathlines under EMS effect as modelled in the digital twin.

Outputs include shell thickness evolution, heat flux distributions, meniscus stability maps, slag film development, infiltration velocities, and friction/lubrication indexes, allowing users to identify breakout risks, surface quality issues, and nonuniform gap behaviour. Together, these capabilities provide a digital representation of the continuous casting mould that closely mirrors real operational conditions.

2.4.2. Validation

The digital twin has been validated against multiple types of industrial measurements, confirming its accuracy and robustness for operational use.

Nail board tests showed that the predicted surface velocities at the metal level closely match measured nail imprints, demonstrating reliable modelling of meniscus flow and jet dynamics. Etched shell thickness profiles from plant trials align with the model's predicted solidification patterns, confirming the correctness of the thermal–metallurgical coupling. Cooling water temperature differences correlate well with simulated heat flux profiles, reinforcing the model's ability to capture real thermal behaviour. Slag infiltration behaviour predicted by the model, including nonuniform drainage and transient variation, agrees qualitatively with known plant observations regarding lubrication variability and oscillation mark formation.

A detailed validation was performed with Sidenor's billet caster as a test case, using a high-resolution mesh (~1 million cells) to resolve meniscus dynamics, EMS induced flow patterns, slag infiltration, and early shell formation. The model successfully reproduced the spiral rotational flow generated by EMS, the meniscus deformation driven by turbulent jet interaction, the spatial variation of the slag film formation, and the shell surface texture influenced by oscillation and withdrawal.

These comparisons confirm that the digital twin behaves as a predictive, industrial grade representation of continuous casting mould physics beyond being a purely academic model.

2.4.3. Success in process optimization

Across multiple RFCS projects and industrial implementations, the digital twin has demonstrated significant value as a process optimisation tool. Its success lies in its ability to test alternatives, evaluate sensitivity to parameters, and identify root causes of performance issues with high physical fidelity.

Optimization has been done for SEN and mould flows, resolving jet penetration, spreading, turbulence intensity, and resulting meniscus motion. This has supported optimisation of SEN port angles, wall thicknesses, and submergence depths to improve flow symmetry and reduce slag entrainment risks.

By resolving shell shrinkage, ferrostatic pressure, and contact conditions, the digital twin helps to refine mould taper to reduce friction, avoid sticking, and improve hot face temperature uniformity. This leads to smoother strand withdrawal and reduced breakout likelihood.

Explicit modelling of slag melting, viscosity changes, and infiltration has enabled data driven selection of mould powders that ensure stable lubrication and controlled heat transfer. This is particularly valuable when switching grades or addressing powder related surface defects.

Simulations define the safe operational window for increasing casting speed while maintaining shell safety margins. Users can virtually test speed changes along with spray cooling strategies and heat flux distributions to avoid overheating or uneven solidification.

The twin reliably captures the effects of electromagnetic stirring on flow patterns and turbulence. This supports tuning of EMS frequency, intensity, and coil placement to enhance mixing without destabilising the meniscus.

By visualising lubrication failures, gap contact zones, stagnation regions, and unstable meniscus behaviour, the digital twin identifies conditions leading to longitudinal cracks, oscillation mark defects, and potential breakouts—enabling targeted operational interventions.

2.5. The SUPPORT-CAST project

2.5.1. Aim and general scope of model

The SUPPORT-CAST project is an EU funded initiative under the Research Fund for Coal and Steel (RFCS) aimed at improving the reliability and quality of steel casting through enhanced digital support during production (RFCS-2016-754130). Its primary objective is to develop online monitoring systems and numerical models capable of identifying defect formation during the continuous casting process [7]. This early detection enables operators to make more informed real time decisions, ultimately leading to safer, more efficient, and higher quality steel production.

2.5.2. Validation

Validation of the SUPPORT-CAST technologies occurs through industrial scale testing at partner production sites, where the newly developed monitoring systems and numerical models are integrated into real continuous casting operations. Project meetings—such as the one reported during the third consortium meeting—highlight ongoing evaluations of system performance in real industrial environments in Spain, confirming active verification of data accuracy, sensor robustness, and model predictions under true production conditions.

The validation process builds on a combination of advanced modelling, in mould sensor technologies, and AI supported prediction tools. These complementary projects demonstrate the broader feasibility and value of machine learning based defect prediction and digital twin methodologies in continuous casting.

Cross project synergies with other projects such as SUNSHINE and RealTimeCastSupport strengthen the technical foundation for SUPPORT-CAST, offering shared benchmarks and best practice frameworks for validating predictive models, sensor integration strategies, and operator support functionalities. Moreover, process control innovation, defect reduction modelling, and sensor enhanced monitoring are among the key validated research directions driving the modernization of Europe's steel sector.

2.5.3. Success in process optimization

The SUPPORT-CAST project was a success in both in the development and deployment of its monitoring and modelling tools. The newly developed systems have enabled to improve operator decision making by providing better insight into defect forming conditions during continuous casting.

By integrating advanced monitoring, modelling, and operator support technologies, SUPPORT-CAST contributes to establishing smarter, safer, and more resource efficient steel casting operations across Europe. Its early success demonstrates the practical impact of RFCS driven digital transformation in a core industrial process, supporting both strategic EU sustainability objectives and the steel industry's need for higher productivity and reduced waste.

2.6. The NNEWFLUX project

2.6.1. Aim and general scope of model

The EU-funded project NNEWFLUX (RFCS-2016-754186) focuses on minimizing slag entrainment without sacrificing mold lubrication during continuous casting of steel through shear-thinning casting powder and developing a Digital Twin to evaluate casting powder performance virtually. This Digital Twin integrates multiphase turbulent flow, heat transfer, solidification, magnetohydrodynamics, solid mechanics, and chemical kinetics, providing a comprehensive simulation environment for casting operations.

The NNEWFLUX project has successfully delivered a powerful Digital Twin for continuous casting, providing deep insight into non-Newtonian mould flux behavior and its effect on casting stability and steel quality. Through advanced multiphysics modelling, validation against real process phenomena, and integration with digital manufacturing technologies, NNEWFLUX enhances operational flexibility, reduces industrial risks, and supports the steel sector's ongoing transition toward smarter, more efficient production.

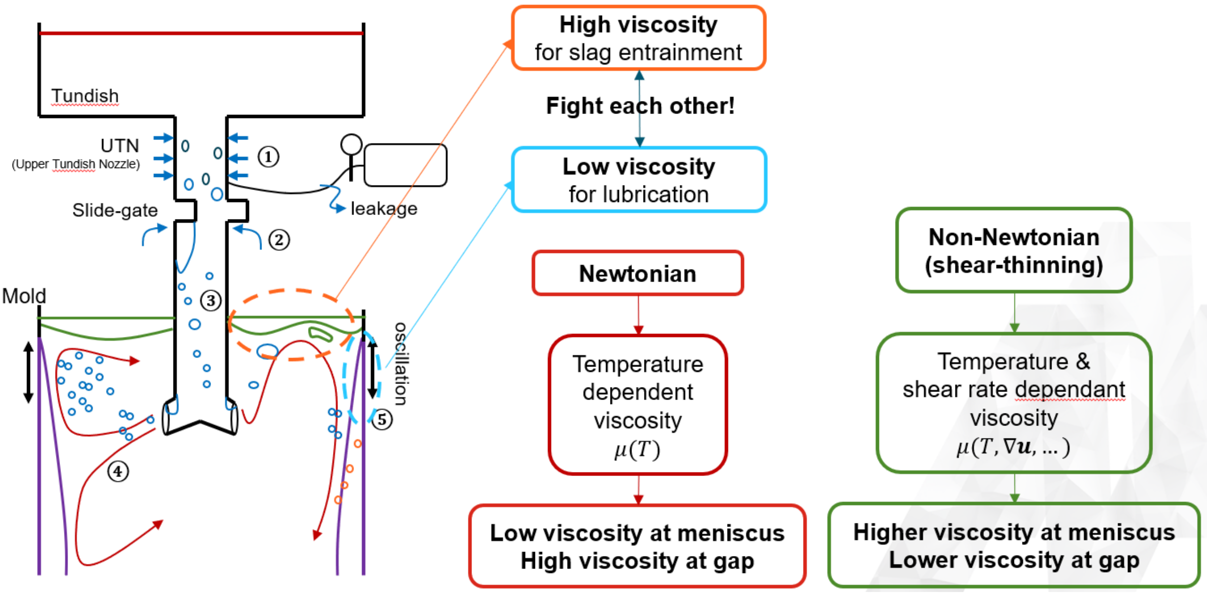


Figure 5. NNEWFLUX project scheme.

2.6.2. Validation

The Digital Twin created in NNEWFLUX was validated through comparisons with measured casting phenomena, especially slag infiltration transitions and related thermal and flow responses. These are key indicators of mould performance and sensitivity to flux viscosity, lubrication characteristics, and entrapment risk [8].

Validation was performed across several dimensions:

- Physical accuracy: The model successfully reproduced complex coupled phenomena—turbulent flow, heat transfer, solidification behaviour, interfacial slag movement, and magnetic effects—mirroring real casting conditions.
- Industrial relevance: The Digital Twin demonstrated capability to simulate arbitrary steel grades and flux chemistries, providing access to variables impossible to measure directly under industrial conditions.

- Reduced need for plant trials: By enabling realistic virtual experimentation, the model replaces time consuming and expensive shop floor tests, improving process safety and cost efficiency.

2.6.3. Success in process optimization

NNEWFLUX delivered significant benefits to continuous casting optimization, particularly by enabling data driven decisions and deeper understanding of flux behaviour:

By integrating all major physical phenomena, the Digital Twin allows an improved operational control via an optimization of casting speed, heat flux balance, and lubrication conditions. The model helps identify the operational windows that minimize surface defects and instability, especially in steels prone to slag entrapment.

Through visualization and prediction of slag infiltration and viscosity dependent flux responses, the model supports strategies to reduce oscillation mark defects, lubrication failures, and interfacial instability—all of which directly affect product quality.

The Digital Twin's ability to connect with IoT systems, sensors, and AI analytics makes it a cornerstone for smart casting systems in times of digital manufacturing. It supports real time monitoring, autonomous decision making, and virtual commissioning of new casting setups. This aligns with RFCS priorities in factory wide control, digitalization, and sustainable manufacturing.

NNEWFLUX allows steelmakers to test transitions between grades and flux compositions virtually, significantly reducing the risks associated with introducing new steel types or process changes. It also supports benchmarking of mould powders, enabling faster adoption of improved formulations.

3. SUMMARY AND OUTLOOK

This report has presented a comprehensive overview of six different cases where modelling the continuous casting process has had success in industrial use and optimization of the process.

These models are toolsets that bring deep insight into the complex interactions of flow, heat transfer, solidification, and lubrication inside the continuous casting process from tundish, through the submerged entry nozzle to the mould. Validated against plant data and successfully applied in real industrial environments, they provide a powerful platform for process optimisation, troubleshooting, and strategic decision making. Their demonstrated capability to reduce operational risks, enhance product quality, and optimise casting parameters underlines the value of modelling as an important technology for steel producers seeking reliable digital process control.

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