Optimisation of production and quality improvement with computational fluid dynamics in the steelmaking industry

Monika Zielińska[1,2], Hongliang Yang[3], Łukasz Madej[2], Łukasz Malinowski[1]
[1] Corporate Technology Center CTC, ABB Sp. z o. o., Zeganska 1 st., 04-713 Warsaw, Poland
[2] AGH University of Science and Technology, Department of Applied Computer Science and Modelling, Mickiewicza 30 av., 30-059 Krakow, Poland
[3] ABB AB/Metallurgy, Terminalvagen 24, Bldg 340, Vasteras 72159, Sweden
monika.zielinska@pl.abb.com, hongliang.yang@se.abb.com,
lmadej@agh.edu.pl, lukasz.malinowski@pl.abb.com

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1. Introduction

The steelmaking industry is one of the crucial industries in the world, where increasing requirements regarding the quality of the final products and environmental regulations force the continuous development and optimisation of production to obtain high efficiency with reduced power consumption. Moreover, each device in the production line must be properly designed to avoid the risk of the faults like improper solidification and sedimentation.

Optimisation of the process during production focused on quality improvement based on the high cleanliness of the steel [1,2] is difficult to carry out in real conditions. Often, the water models in a laboratory scale are used, but the main disadvantage of the method is that the preparation of the test equipment and hence, the design changes are time-consuming. Moreover, all of the phenomena occurring in the real melt are impossible to be covered by water models. Therefore, the numerical approaches to support the experimental investigation and simulate the phenomena in the molten steel are being intensively developed. The simulations from Computational Fluid Dynamics (CFD) domain enable understanding of the processes inside the melt, like the flow distribution, the efficiency of the mixing and the behaviour of the non-metallic inclusions. At the same time, such analysis tools allow optimisation of the manufacturing technology to increase its efficiency. Furthermore, based on the analysis of the flow, the prevention of faults can be realised via the reduction of dead zones and clogging [3]. Nowadays, different methods like the injection of argon gas [4–6], baffle walls (dams, weirs), and dedicated devices like electromagnetic stirrers [7,8] are under development to increase the mixing process and hence, the quality of the steel. All of the mentioned concepts can be easily tested via numerical methods without the long-lasting and expensive laboratory tests or industrial trials.

Within the presented work, the process of secondary steelmaking for continuous casting is taken into consideration, as it significantly influences the final product's quality. The analysis is focused mainly on the ladle furnace and tundish, the two last manufacturing steps before casting, where the high cleanliness of the steel is required. The current analysis includes the implementation of the CFD methods to track the flow behaviour, mixing process and an introduction to the inclusions modelling to understand the mechanisms of its removal phenomenon. The developed

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numerical model can be used as a base for its future improvement and correlations of the results with the real test measurements.

2. Methodology

The research is focused on the CFD approach to simulate phenomena occurring in molten steel during steelmaking. The analysis covers the flow behaviour of the melt, including the mixing process and non-metallic inclusions modelling mainly in the ladle furnace and tundish. Different types of additional stirring are used during the investigation to improve the flow distribution, avoid the dead zones, and increase the amount of the inclusions removed from molten steel. For both, ladle furnace and tundish, the electromagnetic stirring with different electromagnetic power can be considered. The processes in the ladle furnace include gas stirring and a combination of gas and electromagnetic stirring, but mixing in the tundish can be accomplished by baffle walls which are commonly used.

2.1. Electromagnetic stirring

The electromagnetic stirring in the CFD approach is realised as an additional momentum source, where the dependence between the electromagnetic forces and velocity is considered:

$$\vec{F} = \vec{F}_0\left(1 - \frac{\vec{F}_0 \cdot \vec{V}}{2\tau f \cdot |\vec{F}_0|}\right) \tag{1}$$

where: $\vec{F}_0$ – stirring force calculated for stationary melt [N/m^3], $\vec{F}$ – stirring force after compensation with moving melt [N/m^3], τ – pole pitch [m], f – frequency [Hz], $\vec{V}$ – velocity of melt [m/s].

Obtained forces are then interpolated on the fluid domain in each direction, and the whole process is realised by the user-defined scripts implemented in the comercial software.

2.2. Gas stirring

The gas stirring is realised by the multiphase approach, where both, Euler and Lagrange approaches are included. The main assumption is based on the Eulerian VOF (Volume of Fluid) model, where the phase of the molten steel, slag and air can be tracked. The approach enables understanding the behavior of the free surface in the ladle under the stirring process, but does not cover the inert gas behavior. To implement the gas bubbles and its influence on the flow, hence the slag and free surface layer, the Lagrangian DPM (Discrete Phase Model) is applied. Due to the complexity of the phenomena and inert gas bubbles behavior, some simplifications are included like the assumption of the ideal gas, where the diameter of the bubbles is changing with the height. Moreover, the bubbles have a constant mass during the whole process and are removed from the simulation when touching the free surface of the melt. Therefore, the coalescence and breakup of bubbles are not included at this stage and will be developed in the future.

2.3. Non-metallic inclusions modelling

The measurements of the non-metallic inclusions are difficult to realise due to the very expensive apparatus and the necessity to analyse the results in real conditions. Advanced CFD methods enable understanding the behavior of the inclusions and improve the possibilities to reduce its amount in the molten steel. The tracking of the aggregation of non-metallic inclusions is realised by the additional multiphase module PBM (Population Balance Model). The PBM is based on the definition of different sizes of the particles corresponding to different bins, which are tracked during the simulation. The concentration of the bins changes in time according to the aggregation process controlled by the following phenomena:

- Brownian collisions,
- Stokes collisions,
- Turbulent collisions.

Moreover, the inclusions can be removed when they reach the slag layer under special conditions like the proper value of relative velocity between the slag and inclusion, collision time and rupture time.

3. Results and discussion

The research results include the analysis of the flow behaviour on the velocity vectors distribution under different types of stirring, mainly electromagnetic stirring, which is being intensively developed due to the noticeable increase in the mixing process and prevention of the dead zones. The results are obtained for the two important parts of the continuous casting process namely the ladle furnace and tundish, where the high mixing and cleaning occurs. Based on the CFD simulations, the clogging of the outlets is tracked by RTD (Residence Time Distribution) curves to understand the problem and optimise the device construction. Moreover, complex phenomena like inclusions modelling are implemented, which enable understanding the issues with the appearance of the non-metallic inclusions above critical diameters. Obtained data is analysed separately to improve the effectiveness of the whole process and prepare more advanced and efficient solutions.

4. Conclussions

The research confirms the importance of the CFD methods in the steelmaking industry, where the real tests are difficult to carry out due to the high temperature and costs of the measurement equipment. Thanks to the numerical simulations, the optimisation of the production line can be realised.

The strong mixing process without high power input is realised by electromagnetic stirring, which enables to increase the efficiency of the mixing, the homogeneity of the steel structure and the cleanliness of the steel.

The presented numerical approach will be still further developed to obtain better results, validated with real industrial tests.

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