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Editorial

Modeling and Simulation of Metallurgical Processes in Ironmaking and Steelmaking

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1. Introduction and Scope

The UN's 2030 Sustainable Development Goals, the Paris Agreement, and the European Green Deal, among other goals, all aim to improve the sustainability of industrial production and reduce CO_2 emissions. The European Union, for example, aims to reach carbon neutrality and a circular economy by 2050. This goal cannot be achieved without a significant reduction in the CO_2 emissions created by the steel industry. To reach this goal, further process optimizations regarding energy and resource efficiency, as well as the development of new processes or process routes, are needed.

The parameters necessary for the analysis and optimization of the existing and new metallurgical processes in ironmaking and steelmaking often cannot be measured directly because of the harsh conditions inside the furnaces and metallurgical vessels. Typically, the direct information sources in ironmaking and steelmaking are off-gas analysis and spot measurements, which suffer from the delay associated with the analysis of the sample. Due to the harsh environment, opportunities to determine the flow conditions in the vessels by measurements are even more limited. While new methods for the direct and continuous measurement of some of these parameters are under development, for many processes, they are currently unavailable. Furthermore, plant trials that would be necessary to evaluate the impact of different optimization strategies may be impossible because of the prohibitive cost or safety concerns.

Modelling and simulation have established themselves as an invaluable source of information regarding otherwise unknown process parameters, and as an alternative to plant trials with a lower associated cost, risk, and duration. Models are also applicable for model-based control of metallurgical processes.

This Special Issue aimed to cover recent advances in the modelling and simulation of unit processes in ironmaking and steelmaking. To this end, fourteen articles have been published in the present Special Issue of *Metals*. The articles give voice to a total of 67 authors, representing affiliations from ten countries (Figure 1a) with the majority of contributions originating from universities (Figure 1b). The subjects include reviews on the fundamentals of modelling and simulation of metallurgical processes, as well as the fields of iron reduction/ironmaking, steelmaking via the primary and secondary route, and continuous casting.

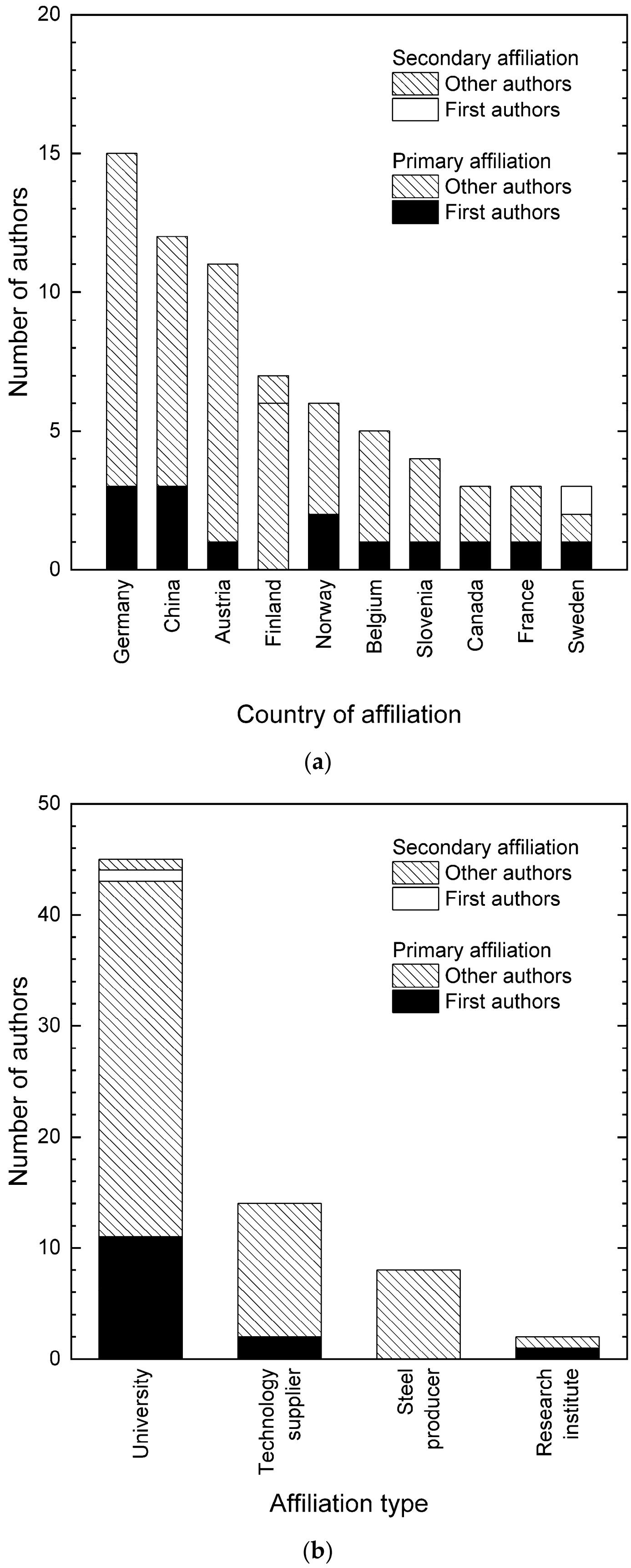

Figure 1. Authors of the contributions of the Special Issue: (**a**) by country of affiliation; (**b**) by affiliation type.

2. Contributions

The fundamentals of modelling and simulation are covered by several articles. Wang et al. [1] review the application of turbulence modelling in metallurgical applications. The article focuses on the validation of models by experiments and the applicability of models to industrial cases. Bubble-induced turbulence, supersonic jet transport, and electromagnetic suppression of turbulence are three specific flow problems discussed in the article. Haas et al. [2] present "A Review of Bubble Dynamics in Liquid Metals". The article presents a detailed discussion of the state of knowledge of bubble dynamics in liquid metals, measurement methods, and bubble formation mechanism at nozzles and purging plugs, and discusses modelling uncertainties using the steel ladle as an example. It is concluded that, while a lot of valuable information has been extracted from both aqueous and liquid metal systems, there are still plenty of uncertainties regarding the behaviour of bubbles in liquid steel. The uncertainties highlighted in the paper include the effect of impurities present in steel, the interaction of gas bubbles in bubble swarms, and the deformation of bubbles due to injectors or walls.

Three articles explore the reduction processes in ironmaking. Quatravaux et al. [3] investigated the Midrex NGTM process and adapted a blast furnace operating diagram to describe the direct reduction of iron oxide in the Midrex shaft furnace. The authors employed the developed graphical tool for a sensitivity study of the reduction in the shaft furnace. Wang et al. [4] present a combination of numerical and experimental investigations of the charging of carbon composite briquettes in a blast furnace. The authors studied the replacement of ore by the carbon composite briquettes and report on carbon conversion, coke rate, blast furnace operation, and productivity, etc. Liu et al. [5] studied the reduction process within a pre-reduction rotary kiln employing numerical simulation methods. The numerical model was validated based on measurement data and then used to investigate process details such as temperature gradients or the progress of the reduction process within the rotary kiln.

The field of steelmaking is covered by eight articles. The first two are more related to the primary steelmaking route, including the blast furnace and basic oxygen furnace while the following five concern steelmaking in the electric arc furnace (EAF). The final article addresses the overarching topic of steelmaking slags. Linnestad et al. [6] report on the development of a process model describing the Composition Adjustment by Sealed argon bubbling with Oxygen Blowing (CAS-OB) process. In this study, a simplified mathematical model for the heat-up stage of the CAS-OB process was coupled with adaptive estimation of state variables using a Kalman filter. The authors present the model's capabilities, as well as model results from the prediction of a data series with more than 1000 heats based on the model implementation at two CAS-OB stations at SSAB Europe Oy in Raahe, Finland. The predicted temperature profiles are displayed for the operator to assist in their decision-making, thus helping to reduce the number of rejected heats. Gao et al. [7] investigated the melting of scrap in hot metal and determined mass transfer coefficients during scrap melting based on laboratory-scale experiments. Subsequently, the authors determined the influence of the variables molten pool stirring rate, bath temperature, and scrap type on the mass transfer coefficient. Tomažič et al. [8] studied the optimization of the energy consumption in an EAF employing data-driven modelling approaches. The models were developed and validated based on industrial data from an EAF steel plant and were used to determine the optimal duration of the transformer profile during melting to reduce energy consumption, thereby increasing EAF efficiency. Jawahery et al. [9] present a first-principles-based process model of the EAF steelmaking designed for online real-time optimization of the process. The model focuses on the integration of auxiliary process data to predict energy efficiency and heat transfer limitations in the EAF. The model was validated using steel temperature and weight measurements achieving reasonable agreement. Al Nasser et al. [10] developed a simplified arc impingement model to study the direct-current electric arc in computational fluid dynamics simulations. The model was used to investigate the influence of the factors arc gap, the density of the gas and total electric current on the behaviour of the arc, and the overall process, including arc impingement depth, velocity magnitude, and arc stability. Reimann et al. [11] investigated statistical modelling approaches based on operational data from five industrial-size EAFs for the prediction of the electric energy demand. Results of the modelling approaches applied to the different industrial EAFs are presented, compared and differences are discussed. Schubert et al. [12] describe the development of a fast modelling approach that was subsequently used to simulate and predict the scrap preheating of a continuously charged EAF. Modelling applications, assumptions, possible enhancements, and limitations, as well as initial simulation results, are presented and discussed. Finally, Safavi Nick et al. [13] studied the modelling and simulation of slag heat recovery to design an optimized heat recovery system. The simulation focused on the heat exchanger and fluid medium used to transfer the heat. This study is a good example of how modern computational fluid dynamics (CFD)-based simulation tools can be used as a design tool for heat recovery processes.

The final field – covered by one article – is continuous casting. Guthrie and Isac [14] present a historical review of casting methods used for sheet steel production. The review shows the development from conventional continuous casting to thin-slab casting as well as different concepts of direct strip casting, and discusses the pros and cons of current methods.

3. Conclusions and Outlook

A variety of connected topics have been compiled in the present Special Issue of *Metals*, providing an overview of recent developments in different aspects of modelling and simulation of metallurgical processes in ironmaking and steelmaking. Despite being a long-term research interest, modelling and simulation could become even more important with the upcoming transformation to carbon-neutral ironmaking and steelmaking processes.

As Guest Editors of this Special Issue, we are very pleased with the contributions received and hope that the presented articles will be useful to researchers and operators of metallurgical plants working to optimize plant operation. We would like to thank all the authors for their contributions, as well as all reviewers for their efforts in maintaining the high quality of published papers. We would also like to give special thanks to all staff at the *Metals* Editorial Office, especially to Toliver Guo, Assistant Editor, who managed and facilitated the publication process of this Special Issue.

Conflicts of Interest: The authors declare no conflict of interest.

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