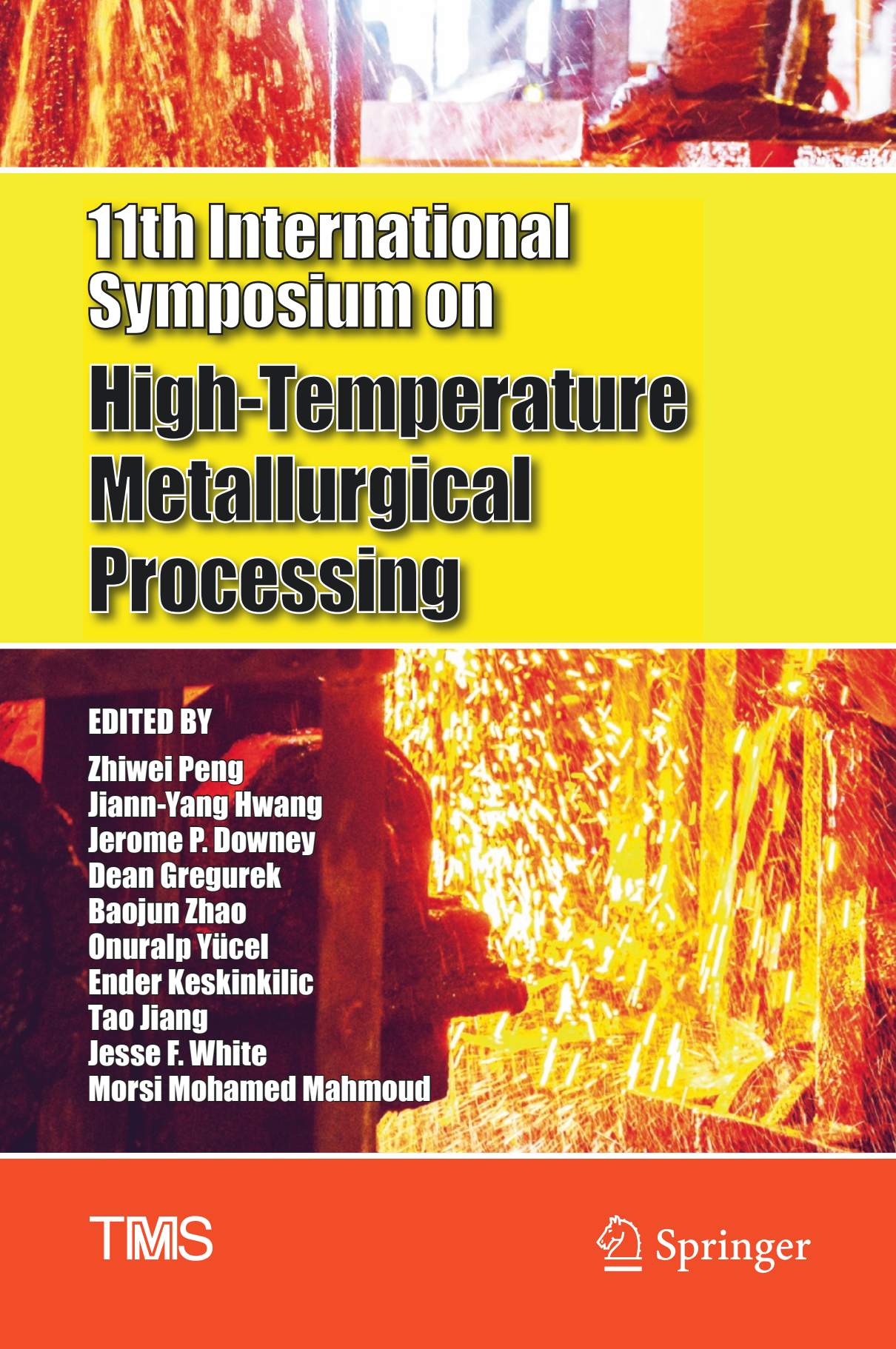




11th International Symposium on High-Temperature Metallurgical Processing

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The Minerals, Metals & Materials Series

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Jerome P. Downey · Dean Gregurek ·
Baojun Zhao · Onuralp Yücel ·
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Preface

This book presents selected papers submitted for the 11th International Symposium on High-Temperature Metallurgical Processing organized in conjunction with the TMS 2020 Annual Meeting and Exhibition in San Diego, California, USA. More than 120 abstracts were received. After reviewing them and the submitted manuscripts, over 90 were accepted for publication in this book.

As the title of the symposium suggests, the interest of the symposium is on thermal processing of minerals, metals, and materials that intends to promote physical and chemical transformations of materials to enable the extraction and production of valuable materials such as metals, alloys, ceramics, and compounds. The symposium was open to participants from both industry and academia and focused on innovative high-temperature technologies including those based on non-traditional heating methods as well as their environmental aspects such as handling and treatment of emission gases and by-products. Because high-temperature processes require high-energy input to sustain the temperature at which the processes take place, the symposium addressed the needs for sustainable technologies with reduced energy consumption and lowered emission of pollutants. The symposium also welcomed contributions on thermodynamics and kinetics of chemical reactions, phase transformations that take place at elevated temperatures, as well as simulation of high-temperature metallurgical processes. We hope the book will serve as a reference for both new and experienced metallurgists, particularly those who are actively engaged in exploring innovative technologies and routes that lead to more energy-efficient and environmentally sustainable solutions.

We would like to acknowledge the contributions from the authors of included papers, the time and effort that reviewers dedicated to the manuscripts, and the help from the publisher. We also thank Dr. Foquan Gu for his help in identifying and screening manuscripts.

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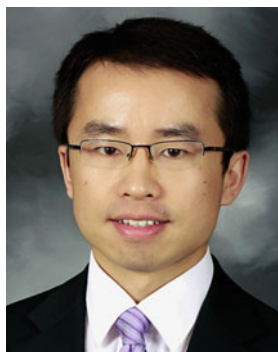
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Dr. Peng has published more than 120 papers, including more than 80 peer-reviewed articles in journals such as *International Materials Reviews*; *Journal of Hazardous Materials*; *ACS Sustainable Chemistry & Engineering*; *Resources, Conservation & Recycling*; *Journal of Cleaner Production*; *Metallurgical and Materials Transactions A*; *Metallurgical and Materials Transactions B*; *JOM*; *Journal of Power Sources*; *Fuel Processing Technology*; *Energy & Fuels*; *IEEE Transactions on Magnetism*; *IEEE Transactions on Instrumentation and Measurement*; *Ceramics International*; *Powder Technology*; and *Separation and Purification Technology*. He has served as a Guest Editor for *JOM* since 2013 and as an Editor for *PLOS ONE* and *Cogent Chemistry* since 2018. He has been a member of the editorial boards of *Journal of Minerals and Materials Characterization and Engineering* since 2012 and *Scientific Reports* since 2019, and has served as a reviewer for more than 50 journals. He received a TMS Travel Grant Award for the 141st TMS Annual Meeting

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Dr. Peng is an active member of The Minerals, Metals & Materials Society (TMS). He has co-organized 8 TMS symposia (Characterization of Minerals, Metals, and Materials in 2013–2018, and the 9th and 10th International Symposia on High-Temperature Metallurgical Processing in 2018 and 2019) and co-chaired 20 TMS symposia sessions since 2012. He is a member of the Pyrometallurgy and Materials Characterization Committees and was the Chair of the Continuing Education Sub-Committee of the Materials Characterization Committee. He was a winner of the TMS EPD Young Leaders Professional Development Award in 2014.



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Onuralp Yücel completed his technical education with a Ph.D. in Metallurgical Engineering from Istanbul Technical University (ITU) where he has held the position of Professor since 2002. He was a Visiting Scientist at Berlin Technical University between 1987 and 1988. He carried out post-doctoral studies at New Mexico Institute of Mining and Technology, Socorro, USA between 1993 and 1994. Dr. Yücel has as many as 330 publications/presentations to his credit, which include topics such as technological developments in the production of a wide range of metals, ferroalloys, advanced ceramic powders, and the application of carbothermic and metallothermic processes among others. He was the Vice Chairman of the ITU Metallurgical and Materials Engineering Department (MMED) between 2004 and 2007, Director of the ITU Applied Research Center of Material Science & Production Technologies between 2006 and 2012, and Chairman of the ITU MMED between 2016 and 2018.

Dr. Yücel is a member of the international advisory board of International Symposium on Boron, Borides, and Related Materials (ISBB), and has been a Co-organizer of the TMS International Symposium on High-Temperature Metallurgical Processing. He also has been involved with the International Symposium on Self Propagating High-Temperature Synthesis (SHS) and International Metallurgy and Materials Congress (IMMC).

Dr. Yücel's areas of interest include:

- Pyrometallurgy: Pretreatment of concentrates (production of WO_3 , Sb_2O_3 , As_2O_3 , MoO_3); smelting and reduction of slags; production of ferroalloys, alloys, and metals carbothermic and metallothermic processes in EAF or in ladle (copper, cobalt, vanadium, chromium, ferroboration, cobalt boron, nickel boron, ferromolybdenum, ferromanganese, silicomanganese, ferrovandium, ferrotungsten, ferrochromium, nickel–chromium–molybdenum–iron and aluminum–titanium–boron alloys).
- Ceramic powder production and processing: Production of carbide, nitride, boride powders, and their processing by explosive consolidation or sintering techniques (B_4C , TiB_2 , ZrB_2 , SiC , CrB_2).

- Beneficiation of industrial wastes: Production of metals and compounds from galvanizing ash, brass production wastes, and vanadium sludges produced aluminum production; grit production from aluminum, copper, and steel slags.



Ender Keskinilic earned his undergraduate degree from the Department of Metallurgical and Materials Engineering of Middle East Technical University (METU), Ankara (the capital city of Turkey), in 1999. He continued his M.S. and Ph.D. studies in the same department. He worked as a Research Assistant at METU between 1999 and 2003. After receiving his master's degree in 2001, he progressed further in the field of extractive metallurgy. During the Ph.D. period, he moved to Eregli-Zonguldak in 2003 and worked in the Quality Metallurgy and RD Department of Eregli Iron and Steel Works Co. (ERDEMIR), the leading steel company in Turkey in terms of production capacity. After earning his Ph.D. degree in 2007, he returned to university to work in the Department of Metallurgical and Materials Engineering of Atılım University, Ankara, in 2008. He has been working as a faculty member there since then. He was Assistant Professor between 2009 and 2014. He has been working as an Associate Professor since 2014. His primary field of interest is extractive metallurgy, and more specifically, pyrometallurgical processes such as ironmaking and steelmaking, ladle metallurgy, ferroalloy production, and non-ferrous extractive metallurgy. He has been acting as the Chairman of the Department of Metallurgical and Materials Engineering of Atılım University since July 2018.



Tao Jiang received his M.S. in 1986 and Ph.D. in 1990, both from Central South University of Technology. Then he joined the university and served as an Assistant Professor (1990–1992) and Full Professor (1992–2000). From 2000 to 2003, he was a Visiting Scientist in the Department of Metallurgical Engineering at the University of Utah. Since 2003, Dr. Jiang has been a Professor in the School of Minerals Processing and Bioengineering at Central South University. He was elected as Specially Appointed Professor of Chang Jiang Scholar Program of China in 2008 and has been the Dean of the School since 2010. His research interests include sintering, pelletizing and non-coke ironmaking of iron ores, and extraction of refractory gold ores. He has completed more than 50 projects from government and industry, including the National Science Fund for Distinguished Young Scholars Program. He and co-workers invented the direct reduction process of composite binder pellets, and three plants were set up in China based on the invention. He proposed the innovative composite agglomeration process of iron ore fines, which was put into production in Baotou Steel Company, China. He has been actively involved in the areas of utilization of non-traditional ferrous resources such as complex ores and various solid wastes. Dr. Jiang has published more than 300 technical papers, and six books including *Direct Reduction of Composite Binder Pellets and Use of DRI*, *Principle & Technology of Agglomeration of Iron Ores*, *Chemistry of Extractive Metallurgy of Gold*, and *Electrochemistry and Technology of Catalytical Leaching of Gold*. He holds 42 patents and has more than 40 conference presentations.



Jesse F. White holds a Ph.D. in Materials Science and Engineering from the KTH Royal Institute of Technology, an M.Sc. in Metallurgical and Materials Engineering from the Colorado School of Mines, and a B.S. in Metallurgical Engineering from the South Dakota School of Mines and Technology. He began his career in 1996 as a Process Engineer at the Kaiser Aluminum Mead Works. In 1997, he moved to Luleå, Sweden, and began as a Research Engineer at MEFOS working mainly in strip casting of steel. In 2002, he moved to Oslo, Norway and spent 5 years at Alstom as a Project Engineer designing, building, commissioning, and troubleshooting gas treatment systems for aluminum smelters around the world. Since 2007, he has been employed by Elkem in Kristiansand, Norway; starting out at Elkem Solar as a Research Engineer specializing in silicon refining, later moving to Elkem Technology, and since 2015 at Elkem Carbon. He is currently Technology Director at Elkem Carbon, supporting the production facilities in Brazil, China, Malaysia, Norway, and South Africa. In parallel, Dr. White is also currently an Affiliated Faculty Member of the Materials Science and Engineering Department at the KTH Royal Institute of Technology in Stockholm, where he teaches thermodynamics and conducts research in the areas of high-temperature experimental thermodynamics and metallurgical reactor design.



Morsi Mohamed Mahmoud joined the Mechanical Engineering Department at King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia, in August 2016. He also holds an Associate Professor position at the Advanced Technology and New Materials Research Institute (ATNMRI), City for Scientific Research and Technological Applications (SRTA City), Egypt. From December 2009 until August 2016, he worked as a Visiting Assistant Professor and then as a Senior Scientist at Institute of Applied Materials—Applied Materials Physics (IAM-AWP) at Karlsruhe Institute of Technology (KIT), Germany. Dr. Mahmoud earned his Ph.D. and M.Eng. degrees in Materials Science and Engineering from Virginia Tech, Blacksburg, USA in 2007. He has accumulated unique experience and skills in advanced materials processing techniques such as microwave

processing, glasses, ceramics, and structure–property–processing relationship in materials, in addition to a deep knowledge in materials characterization techniques. He also has had experience organizing and editing several technical publications, conferences, web-seminars, and scientific events. He is serving as the Chairman and the Organizer of the Processing and Performance of Materials Using Microwaves, Electric and Magnetic Fields, Ultrasound, Lasers, and Mechanical Work at the Materials Science & Technology Technical Meeting and Exhibition 2019 (MS&T19), USA. Furthermore, he served as a Co-editor for nine books and published 32 technical papers in the top 10 ISI ranked journals in Materials Science and Engineering. He was given several prestigious awards such as Virginia Tech Citizen Scholar Award; an Honor Scholarship from Virginia Tech Graduate School, USA; and Two German Academic Exchange Service (DAAD) Fellowships.

Part I

Simulation of High-Temperature Processes

Hydraulic Model Study of Combined Blowing in 65t Electric Arc Furnace (EAF)



Xuetao Wu, Rong Zhu, Guangsheng Wei, Kai Dong and Lingzhi Yang

Abstract A hydraulic model with a similarity ratio of 1:4 was used to simulate the blowing parameters of 65t electric arc furnace (EAF). The molten bath stirring effects of different bottom blowing arrangements and flow rates under different combined blowing conditions were studied. On this basis, orthogonal experiments were designed to study the effects of bottom blowing rate, side blowing rate, and bottom blowing arrangement on the mixing time of molten bath. The results showed that the bottom blowing arrangement has little effect on the mixing time of molten pool. Under the condition of combined blowing, the degree of influencing factors on mixing time from big to small was the side blowing rate, bottom blowing rate, and bottom blowing arrangement. The industrial experiment showed that, compared with traditional process, the combined blowing process can increase the decarbonization rate and reduce the consumption of iron and steel materials.

Keywords Electric arc furnace · Hydraulic model · Combined blowing

Introduction

The electric arc furnace (EAF) has played a very important role in the modern steelmaking process. However, a prominent disadvantage in the process of EAF steelmaking is that the stirring of the molten pool is weak and the smelting time is long. The heat generated by the arc directly heats the molten steel in the upper part of the molten pool, while the molten steel near the bottom and outside the arc zone

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are heated mainly by convective diffusion of heat. The bottom blowing technique for EAF steelmaking process was proposed to promote the molten bath fluid flow, accelerate the metallurgical reaction, and improve the quality of molten steel.

As the EAF steelmaking is a high-temperature and high-pressure process, and it is accompanied by high-power electric energy transmission, water models and numerical simulations have been widely used to study the metallurgical effects of EAF steelmaking [1–4]. Wei [1] established a mathematical model and water model to study the physical and chemical properties of molten bath with bottom blowing, and the results showed that bottom blowing could promote mass transfer and increase the capacity of EAF production. Schade [5] compared the major effects of bottom blowing with traditional melting conditions without bottom blowing in Lukens steel company. Li [6] studied the effect of bottom stirring condition on the rising height of the EAF bath and the mixing characteristics of bottom blowing in EAF through water model experiments. Li [7] studied the fluid flow and mixing process in a bottom stirring EAF experimentally and numerically and found that with the bottom blowing nozzles moving off-center, the angular velocities were increased, and the stirring efficiency was improved significantly.

Combined blowing technology of EAF combines the characteristics of side blowing and bottom blowing of EAF, which can improve the productivity of EAF and the quality of steel, reduce energy consumption. In the present study, a hydraulic model with a similarity ratio of 1:4 was used to simulate the blowing parameters of 65t EAF. The molten bath stirring effects of different bottom blowing arrangements and flow rates under different combined blowing conditions were studied.

Hydraulic Experiment

In this study, a hydraulic model experiment was carried out to analyze the effect of combined blowing on the molten bath stirring in EAF, whose instruments were shown in Fig. 1. The side and bottom blowing gas were injected into the hydraulic bath through three oxygen lance and three porous plugs. The side oxygen lance consisted of stainless steel, while the porous plugs consisted of copper rod and plexiglass. The KCl was applied as the tracer and two conductivity electrodes were set at different locations to record the mixing time by monitoring the hydraulic electronic conductivity in the molten bath. In order to make sure that the experiment results were reliable, two experiments were carried out for each experimental scheme, and the results should deviate less than 10%.

Table 1 lists the dimensions of hydraulic model which was scaled down by a ratio of 1:4. The hydraulic and compressed air were, respectively, used to represent the molten steel and the combined blowing gases (oxygen and argon).

As previously reported, the fluid flow and mixing are caused by momentum transfer by blowing gases and liquids [8–11]. To ensure the similarity between the hydraulic model and real EAF, the modified Froude number of two models should be maintained, and the equations can be expressed by Eqs. (1)–(2).

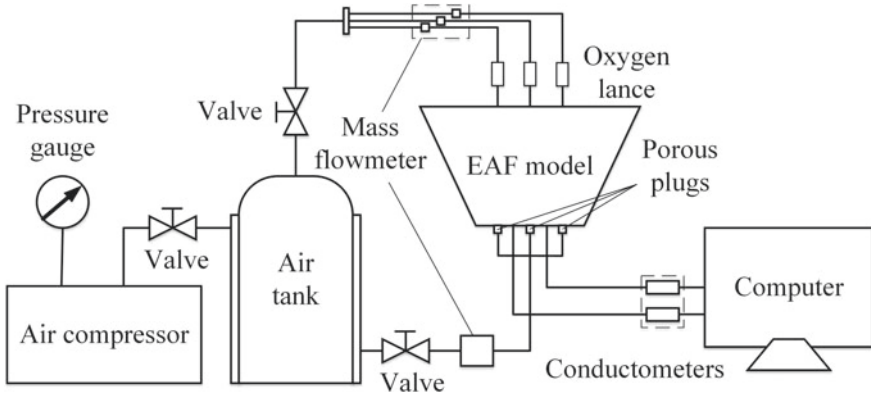


Fig. 1 Combined blowing experimental instruments of hydraulic model experiment

Table 1 Characteristics parameters of prototype and model

Items	Prototype	Hydraulic model
Hydraulic diameter(mm)	2274	568.5
Furnace height(mm)	1700	425
Molten bath depth, H(mm)	1300	325
Lance height(mm)	500	125
Lance angle (°)	45	45
Molten bath density (kg/m ³)	7000	1000
Side blowing gas density (kg/m ³)	1.429	1.293
Bottom blowing gas density (kg/m ³)	1.783	1.293

$$Fr' = Fr'_1, \text{ that is } \frac{\rho_{gp}(\pi/4)d_p^2 u_p^2}{g\rho_{lp}(\pi/4)D_p^2 H_p^2} = \frac{\rho_{gw}(\pi/4)d_w^2 u_w^2}{g\rho_{lw}(\pi/4)D_w^2 H_w^2} \quad (1)$$

$$\frac{Q_p}{Q_w} = \sqrt{\left(\frac{d_p}{d_w}\right)^2 \times \left(\frac{D_p}{D_w}\right)^2 \times \left(\frac{H_p}{H_w}\right)^2 \times \frac{\rho_{lp}}{\rho_{lw}} \times \frac{\rho_{gw}}{\rho_{gp}}} \quad (2)$$

where ρ_{lw} , ρ_{lp} , ρ_{gw} , and ρ_{gp} are, respectively, the liquid density of the hydraulic model, the liquid density of the prototype, the gas density of the hydraulic model, and the gas density of the prototype, kg m⁻³; d_w and d_p are the nozzle diameters of the hydraulic model and the prototype, m; H_w and H_p are the molten bath depth of the hydraulic model and the prototype, m; u_w and u_p are the gas velocities of the hydraulic model and the prototype, m s⁻¹; Q_w and Q_p are the gas flow rates of the hydraulic model and the prototype, m³ h⁻¹; g is the gravity acceleration, m s⁻². D_w and D_p are the molten bath hydraulic diameter of the hydraulic model and the prototype, m, and it can be calculated by Eq. (3).



Fig. 2 The combined blowing arrangements in EAF model

Table 2 Gas flowrates of prototype and model (single node)

	Bottom blowing flow rate (NL · min ⁻¹)	Side blowing flow rate (Nm ³ · h ⁻¹)
Prototype	50/100/150/200	1000/1500/2000
Hydraulic model	1.42/2.12/2.82/3.53	12.4/18.6/24.8

$$D = \frac{\pi \left(\frac{D_1}{2} \times \frac{A}{360} + \frac{D_2}{2} \times \frac{B}{360} \right) + 2 \times L_1}{\pi}, \quad (3)$$

where D is the molten bath hydraulic diameter, m.

The oxygen lance and bottom blowing arrangements are shown in Fig. 2, four different bottom blowing arrangements (A1A2, A1B2, B1A2, and B1B2) will be analyzed in this study. Based on Eqs. (1)–(3), the parameters of combined blowing are shown in Table 2.

In this study, the mixing time was defined as the time when the conductivity between the two electrodes converged and remained stable. The mean mixing time (T_{mix}) was calculated by Eq. (5).

$$T_{mix} = \frac{T_1 + T_2}{2}, \quad (5)$$

where T_1 and T_2 are the mixing time of the two experiments for each experimental scheme, s.