Energy Technology 2019

Carbon Dioxide Management and Other Technologies

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The Minerals, Metals & Materials Series

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Preface

This volume contains selected papers presented at the Energy Technologies Symposium organized in conjunction with the TMS 2019 Annual Meeting & Exhibition in San Antonio, Texas, USA, and organized by the TMS Energy Committee. The papers in this volume intend to address the issues, intricacies, and the challenges relating to energy and environmental science. This volume also contains selected papers from the two other symposia: Solar Cell Silicon and 5th Symposium on Advanced Materials for Energy Conversion and Storage.

The Energy Technologies Symposium was open to participants from both industry and academia and focused on energy-efficient technologies including innovative ore beneficiation, smelting technologies, recycling, and waste heat recovery. The volume also covers various technological aspects of sustainable energy ecosystems, processes that improve energy efficiency, reduce thermal emissions, and reduce carbon dioxide and other greenhouse emissions. The papers addressing renewable energy resources for metals and materials production, waste heat recovery, and other industrial energy-efficient technologies, new concepts or devices for energy generation and conversion, energy efficiency improvement in process engineering, sustainability and life cycle assessment of energy systems, as well as the thermodynamics and modeling for sustainable metallurgical processes are included. This volume also includes topics on CO_2 sequestration and reduction in greenhouse gas emissions from process engineering, sustainable technologies in extractive metallurgy, as well as the materials processing and manufacturing industries with reduced energy consumption and CO_2 emission. Contributions from all areas of nonnuclear and nontraditional energy sources, such as solar, wind, and biomass are also included in this volume.

We hope this volume will provide a reference for materials scientists and engineers as well as metallurgists for exploring innovative energy technologies and novel energy materials processing. We would like to acknowledge the contributions from the authors of the papers in this volume, the efforts of the reviewers dedicated to the manuscripts review process, and the help received from the publisher. We appreciate the efforts of Energy Committee members for enhancing this proceedings volume. We also acknowledge the organizers of the other symposia that contributed papers.

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About the Editors

Tao Wang is the Chief Metallurgist at Nucor Steel. He is the Lead Engineer in the process and product research and development areas. Dr. Wang's current focus is to develop and modify a novel thin strip casting technology, which uses up to 90% less energy to process liquid steel into hot rolled steel sheets than conventional casting methods. Dr. Wang has rich experience in metallurgical thermodynamics, thermal energy storage and transfer, steelmaking, metal solidification and casting, and metal corrosion. He obtained his Ph.D. and M.S. from the University of Alabama and received his B.S. from Xi'an Jiao Tong University in China. In his areas of research, Dr. Wang has published over 20 papers and patents which have led to breakthroughs in thermodynamic modeling, high-efficiency thermal energy transfer medium development, and thin strip metal casting technology. Dr. Wang received the 2017 SME Outstanding Young Manufacturing Engineers from Society of Manufacturing Engineers, and the 2013 Light Metals Division (LMD) Best Energy Paper Award from TMS. He is also the 2016 TMS Young Leaders Professional Development Award winner. Dr. Wang was selected to become a member of TMS Emerging Leaders Alliance in 2015. He serves on the TMS Energy Committee and Pyrometallurgy Committee, and the Metallurgy—Steelmaking & Casting Technology Committee and Continuous Casting Technology Committee, Southeast Chapter within the Association for Iron & Steel Technology (AIST).

Xiaobo Chen earned his Ph.D. from Deakin University in 2010 for his work in materials science and engineering and then joined the Department of Materials Science and Engineering at Monash University as Postdoctoral Research Fellow, DECRA Awardee, and Senior Research Fellow. He joined RMIT as VC Senior Research Fellow in March 2017 and is based in the School of Engineering at City Campus.

His research is multidisciplinary and spans from chemistry and materials science through to corrosion, electrochemistry, and biomaterials, and shows promise in benefitting the wider community. Dr. Chen's research aims to provide functional characteristics to the surface of light metals to satisfy a large range of engineering applications in automotive, 3C, and biomedical industries.

Dr. Chen has attracted extensive research funding from the ARC as the Lead Chief Investigator on a 3-year ARC Discovery Early Career Researcher Award (DECRA) in 2013, a 3-year ARC Linkage grant in 2015, and a 3-year research grant with the ARC Research Hub for nanoscience-based construction materials manufacturing in 2017. He has also worked with the Baosteel-Australia Joint Research and Development Centre and Mitsubishi Heavy Industry on three research contracts.

Donna Post Guillen has more than 30 years of research and engineering experience and has served as Principal Investigator for numerous multidisciplinary projects encompassing energy systems, nuclear reactor fuels and materials experiments, and wasteform development. She is experienced with X-ray and neutron beamline experiments, computational methods, tools and software for data analysis, visualization, application development, machine learning and informatics, simulation, design, and programming. Her core areas of expertise are thermal fluids, computational fluid dynamics, and heat transfer analysis. She has performed irradiation testing of new materials and thermal analysis for nuclear reactor experiments in her role as Principal Investigator/ Technical Lead for the DOE Nuclear Science User Facility Program. She is the lead inventor on two patents for a new metal matrix material to produce a fast neutron flux environment within a pressurized water reactor. She actively mentors students, routinely chairs and organizes technical meetings for professional societies, serves in leadership capacity for the American Nuclear Society (Thermal Hydraulics Executive and Program Committees), The Minerals, Metals & Materials Society (former Chair of the Energy Committee, *JOM* Advisor), and the American Society of Mechanical Engineers (Thermal Hydraulics and Computational Fluid Dynamic Studies Track Co-Chair), provides subject matter reviews for proposals and technical manuscripts, has published over 100 papers and received two Best Paper awards, authored technical reports and journal articles, and written/edited three books.

Lei Zhang is an Associate Professor in the Department of Mechanical Engineering at the University of Alaska Fairbanks (UAF). Prior to joining the UAF, Dr. Zhang worked as a postdoctoral associate in the Department of Chemical and Biomolecular Engineering at the University of Pennsylvania. Dr. Zhang obtained her Ph.D. in Materials Science and Engineering from Michigan Technological University in 2011, and her M.S. and B.E. in Materials Science and Engineering from China University of Mining and Technology, Beijing, China, in 2008 and 2005, respectively. Her current research mainly focuses on the synthesis of metal-organic frameworks (MOFs) and MOF-based nanocomposites, and the manipulation of their properties and applications in gas storage, separation, and water treatment. She is also working on the development and characterization of anticorrosion coatings on metallic alloys for aerospace and biomedical applications.

Dr. Zhang has served on TMS Energy Committee since 2014, including the Vice-Chair role in 2018–2019, and served on a Best Paper Award Sub-committee of the committee. She has served as a frequent organizer and session chair of TMS Annual Meeting symposia (2015–present). She was the recipient of 2015 TMS Young Leaders Professional Development Award.

Ziqi Sun is an Associate Professor and an ARC Future Fellow at the School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, Australia. He received his Ph.D. in 2009 from Institute of Metal Research, Chinese Academy of Sciences and his B.Eng. in 1999 from Central South University China. He was awarded with prestigious awards and fellowships including the TMS Young Leaders Development Award from The Minerals, Metals & Materials Society (TMS, 2015), Future Fellowship (FT2, 2018) and Discovery Early Career Research Award (DECRA, 2014) from Australian Research Council, Alexander von Humboldt Fellowship from AvH Foundation Germany (2009), Australian Postdoctoral Fellowship from Australian Research Council (APD, 2010), and Vice-Chancellor's Research Fellowship from University of Wollongong (2013). He is also serving as Chair of the Energy Committee of TMS, Editor of *Sustainable Materials and Technologies* (Elsevier), Principal Editor of *Journal of Materials Research* (MRS), Associate Editor of *Surface Innovations* (ICE Science), Editorial Board Member of *Scientific Reports* (Nature Publishing Group), and *Journal of Materials Science and Technology* (Elsevier). He was also Guest Professor of Shenzhen Institute, Peking University, and Honorary Fellow of University of Wollongong. Dr. Sun is the program leader for three ongoing Australian Research Council Projects. He held the roles as lead organizer in TMS conferences, ACerS annual conferences, and AM&ST18 symposium. His major research interest is the rational design of bio-inspired metal-oxide nanomaterials for sustainable energy harvesting, conversion, and storage.

Cong Wang is a Professor in the School of Metallurgy, Northeastern University, China. Prior to joining the faculty of his alma mater, he worked in Northwestern University, Saint-Gobain, and Alcoa, all in the United States. He obtained his Ph.D. from Carnegie Mellon University, M.S. from Institute of Metal Research, Chinese Academy of Sciences, and B.S. (with honors) from Northeastern University. He is now leading a group dedicated to oxide metallurgy.

Dr. Wang is an active member and a prolific scholar in the global metallurgy community. He has been recognized with distinctions such as TMS Early Career Faculty Fellow Award, CSM Youth Metallurgy S&T Prize, Newton Advanced Fellowship, JSPS Invitational Fellowship, TÜBİTAK Fellowship, and SME Outstanding Young Manufacturing Engineer Award. He serves as a Key Reader and Vice-Chair for the Board of Review for *Metallurgical and Materials Transactions B*; Review Editor for *Journal of Materials Science and Technology*; Editorial Board Member of *International Journal of Refractory Metals and Hard Materials* and *Journal of Iron and Steel Research, International*; and Corresponding Expert for Engineering. He chaired the TMS Energy Committee from 2016 to 2017. He is the inaugural chair for the ASM Shenyang Chapter, and faculty advisor for Material Advantage Northeastern University. He initiated the International Metallurgical Processes Workshop for Young Scholars (IMPROWYS), and organized major conferences/symposia of technical significance.

Nawshad Haque is a Senior Scientist at the Australian national research agency Commonwealth Scientific and Industrial Research Organization (CSIRO). He is leading a range of projects that evaluates technology for resources industries for saving energy, water and operating costs. Currently his main projects are to study the techno-economic and environmental impacts of hydrogen and ammonia production technologies, fuel cells, off-grid, solar, wind, biomass and hybrid energy systems, and life cycle based emission studies of LNG production. He joined CSIRO Mineral Resources as a Research Scientist (Process Modelling) in 2007. His current research focuses on process, project, and technology evaluation applying life cycle assessment (LCA) methodology and techno-economic capabilities using various tools, software, and databases. He has contributed to develop a number of novel technologies and flowsheets for "Mine to Metal" production and energy processing at CSIRO. His publications and industry reports are widely used internally and externally and assist in decision-making both in Australia and internationally. Dr. Haque completed his Doctorate in Engineering at the University of Sydney on process modeling, simulation, and optimization in 2002. He commenced work as a Research Scientist at New Zealand Forest Research Institute (Scion) and later seconded to CSIRO at Clayton to conduct research on drying process simulation and technology evaluation for industries. He is an active leader in professional societies—an elected Fellow of the Australian Institute of Energy and the Australasian Institute of Mining and Metallurgy, a member of The Minerals, Metals & Materials Society, and a Director of Australian Life Cycle Assessment Society. Dr. Haque has supervised undergraduate and Ph.D. students, and he coordinates and offers mineral processing and life cycle assessment courses for undergraduate students and workshops for professionals. He has a number of international collaborations with the universities and publicly funded research laboratories on mineral, metal processing, energy processing, and sustainability.

John A. Howarter is an Associate Professor in Materials Engineering at Purdue University with a joint appointment in Environmental & Ecological Engineering. His research interests are centered on synthesis, processing, and characterization of sustainable polymers and nanocomposites, value recovery through recycling and reprocessing of waste materials, and sustainable materials which can enable improved design for the environment.

John is Chair of the TMS Public and Governmental Affairs committee and serves on the TMS Board of Directors. Since 2014, he has served as the chapter advisor for the Purdue University Material Advantage student organization. John earned a B.S. from The Ohio State University in 2003 and Ph.D. from Purdue University in 2008, both in Materials Engineering.

From 2009 to 2011, he was a National Research Council postdoctoral scholar in the Polymers Division of the National Institute of Standards and Technology in Gaithersburg, Maryland.

Neale R. Neelameggham is “The Guru” at IND LLC, involved in international technology and management consulting in the field of critical metals and associated chemicals, thiometallurgy, energy technologies, soil biochemical reactor design, lithium-ion battery design, and agricultural uses of coal. He was a visiting expert at Beihang University of Aeronautics and Astronautics, Beijing, China and a plenary speaker at the Light Metal Symposium in South Africa on the topic of low carbon dioxide emission processes for magnesium.

Dr. Neelameggham has more than 38 years of expertise in magnesium production and was involved in process development of the startup company NL Magnesium through to the present US Magnesium LLC, UT until 2011. He and Brian Davis authored the ICE-JNME award-winning (2016) article “21st Century Global Anthropogenic Warming Convective Model.” He is presently developing “stored renewable energy in coal” Agricoal™ for greening arid soils and has authored an e-book *Eco-stoichiometry of Anthropogenic CO2 That Returns to Earth* on a new discovery of quantification of increasing CO2 returns to Earth.

Dr. Neelameggham holds 16 patents and patent applications, and has published several technical papers. He has served in the Magnesium Committee of the TMS Light Metals Division (LMD) since its inception in 2000, chaired it in 2005, and in 2007 he was made a permanent coorganizer for the Magnesium Technology Symposium. He has been a member of the Reactive Metals Committee, Recycling Committee, and Titanium Committee, and was a Program Committee Representative for LMD.

Dr. Neelameggham was the inaugural chair, when in 2008, LMD and the Extraction and Processing Division created the Energy Committee, and he has been a coeditor of the Energy Technology symposium through the present. He received the LMD Distinguished Service Award in 2010. While he was the chair of Hydrometallurgy and Electrometallurgy Committee, he initiated the Rare Metal Technology symposium in 2014. He is coeditor for the 2019 symposia on Magnesium Technology, Energy Technology, Rare Metal Technology, REWAS 2019, and Solar Cell Silicon.

Shadia Ikhmayies received B.Sc. and M.Sc. from the physics department at the University of Jordan in 1983 and 1987, respectively, and a Ph.D. on the topic of producing CdS/CdTe thin film solar cells from the same university in 2002. She now works at Isra University in Jordan as an Associate Professor. Her research is focused on producing and characterizing semiconductor thin films, and thin film CdS/CdTe solar cells. She also works in characterizing quartz in Jordan for the extraction of silicon for solar cells and characterizing different materials by computation. She has published 48 research papers in international scientific journals, 73 research papers in conference proceedings, and 3 chapters in books. She is the author of two books for Springer, *Silicon for Solar Cell Applications* and *Performance Optimization of CdS/CdTe Solar Cells* (both in production), editor of the book *Advances in II–VI Compounds Suitable for Solar Cell Applications* (Research Signpost), the book *Advances in Silicon Solar Cells* (Springer), an eBook series about material science (in development with Springer), and several TMS proceedings publications. She is the winner of the TMS Frank Crossley Diversity Award (2018), and the World Renewable Energy Congress 2018 (WREC-18) Pioneering Award.

Dr. Ikhmayies is a member of the The Minerals, Metals & Materials Society (TMS) and the World Renewable Energy Network (WREN). She is a member of the international organizing committee and the international scientific committee in the European Conference on Renewable Energy Systems (ECRES2015–ECRES2018). She is a member of the editorial board of the *International Journal of Materials and Chemistry* (Scientific & Academic Publishing), and has served as a technical advisor/subject editor for *JOM* (2014 and 2019). She has been a guest editor for topical collections from the European Conference on Renewable Energy Systems in the *Journal of Electronic Materials,* and an editorial advisory board member for *Recent Patents on Materials Science* (Bentham Science). She is a reviewer for 24 international journals, was the Chair of the TMS

Materials Characterization Committee (2016–2017), and has been lead organizer of more than four symposia at the TMS Annual Meeting and Exhibition.

York R. Smith is an Assistant Professor of Metallurgical Engineering in the College of Mines and Earth Sciences at the University of Utah, where he specializes in extractive metallurgy. Growing up in Northern Michigan, his love for snow-covered peaks and open spaces led him to the University of Nevada, Reno where he obtained his B.S. and M.S. in Chemical Engineering. Given his only criterion of decent skiing, he then moved to the University of Utah where he obtained his Ph.D. in Metallurgical Engineering. After a postdoctoral research appointment from the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Dr. Smith joined the faculty of the College of Mines and Earth Sciences at the University of Utah. His current research interests include nonferrous metal recycling, electrochemistry and interfacial phenomena, and sustainable/green metallurgical engineering.

Leili Tafaghodi is an Assistant Professor and the extractive metallurgy industry research chair at the University of British Columbia, Vancouver, Canada. Leili's research is built around the idea of sustainable high-temperature extraction and refining of materials. She obtained her Ph.D. from the University of Toronto and specializes in thermodynamics and kinetics of high-temperature materials processes and synthesis and refining of high-quality metals and alloys.

Amit Pandey is a Manager (Manufacturing Innovation and Integration) at LG Fuel Cell Systems (LGFCS) in North Canton, Ohio. Previously, he was employed at Johns Hopkins University (JHU) and Oak Ridge National Laboratory (ORNL). He is primarily interested in structural and functional materials for energy conversion and storage.

Dr. Pandey received his B.S. (2003) in Mining Engineering from Indian Institute of Technology (IIT–BHU) Varanasi, India. Later, he received his M.S. (2005) in Civil Engineering from University of Arizona and Ph.D. (2010) in Mechanical Engineering from University of Maryland. He has Google Scholar citations ∼700 and has received young leader awards from various materials societies (ACerS, TMS, ASM). In 2017, he was selected to attend the US. Frontiers of Engineering Symposium, National Academy of Engineering, USA.

Part I
2019 Energy Technologies and Carbon Dioxide Management Symposium

Analysis on Energy Efficiency and Optimization of HIsmelt Process

Chao-zhen Cao, Yu-jie Meng, Fang-xing Yan, Dian-wei Zhang, Xin Li and Fu-ming Zhang

Abstract HIsmelt process is a clean and efficient iron-making technology. The production of the first HIsmelt commercial plant of China, which was built in 2016, is stable at present, and remarkable results have been achieved in environmental protection and production cost aspects. The energy efficiency and its main influencing factors of HIsmelt process were systematically analyzed in this paper, combining with China's HIsmelt plant production practice. It has been pointed out that the main restrictive factors are the high efficient utilization of high temperature and low calorific value SRV off-gas to further improve the energy efficiency of HIsmelt. It introduced the process improvement and optimization of the HIsmelt plant in China, around the hot air blast position control, iron ore powder preheating, gas purification, and waste heat recovery.

Keywords HIsmelt · Smelting reduction · Iron-making · Energy efficiency Improvement

HIsmelt process is a typical "one-step" melting reduction process; its reduction and melting process take place in the same vessel, which can directly use powder ore and pulverized coal in. It did not use coke anymore, and the raw materials do not need to be agglomerated. So it is a meaningful smelting reduction process [1]. China's first HIsmelt plant with annual production of 80×10^4 t hot metal was put into operation in 2016, and this plant has achieved significant results in raw material flexibility, environmental protection, and production costs. Compared with blast furnace process, the successful implementation of Chinese HIsmelt plant has a significant and leading role in promoting the development of smelting reduction iron-making technology [2].

HIsmelt process as a representative "metal bath" smelting reduction process, the raw materials were deep injected into the iron bath specially. On the one hand, the

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pulverized coal inject into the iron bath can be directly carburized by the molten iron; on the other hand, under the action of carrier gas the iron bath produces strong stirring; it forms "fountain". The liquid slag and iron droplet splashing after being heated in the upper high-temperature zone, and then returned to the metal bath. The heat generated by off-gas post-combustion continuous transfers to the bath, which can be achieved higher heat transfer efficiency under the higher post-combustion degree, which is a key part of the whole process. Currently, compared with the blast furnace process, there are still some gaps in energy utilization efficiency, which shows that the process energy consumption is higher, so it is important to optimize the energy efficiency of the HIsmelt plant in order to improve the technology competitiveness.

Operation Practice of Chinese HIsmelt Plant

In 2012, Rio Tinto signed a licensing agreement with Chinese companies to build HIsmelt industrial plants in China. In the design and construction periods, this Chinese HIsmelt plant has carried out the improvement and optimization in accordance with the problems occurred on the equipment, technology, and production process in Kwinana plant. After more than 5 years working on process adjustment and equipment optimization, it accomplished continuous stable production in 2017 [3].

Chinese HIsmelt plant started construction in 2013, completed in August 2016, it goes into stable production in September 2017. It has a total of 450,000 tons of high-purity pig iron until March 2018, daily maximum production reached 1930 t; average daily output reached 1685 t in October 2017, monthly output reached 51,714 t, coal consumption per iron tons gradually reduced, it goes to 900 kg/thm during the stable production, and the lowest coal consumption is 810 kg/tHM, close to the reach design value. The molten iron contains less P, the harmful element content is very low, and the quality of pig iron has reached to Chinese high pure pig iron national standard level. SRV lining condition is still good, and the first campaign life of SRV lining has been more than 450,000 tons iron, only a partial repair, especially the slag line part erosion problem has been better resolved [4] (Table 1; Fig. 1).

Table 1 Production indexes of Chinese HIsmelt plant

Items	Index	Time
Daily maximum output	1930 t	2017 year
Monthly maximum output	51714 t	2017 year
Minimum coal consumption	810 kg/tHM	2017 year
Weekly maximum operating rate	100%	2017 year
Continuous production record	116 days	2017 year
Erosion of the lining	45 Mt hot metal	Never changed

Fig. 1 Chinese HIsmelt plant

SRV Heat Balance Analysis

Based on the Chinese HIsmelt plant production practice and technological parameters, the SRV thermal equilibrium is calculated and analyzed, and the calculation is shown in Table 2 (Fig. 2).

As shown in the calculation results, the SRV heat incomes mainly come from the pulverized coal burning, which accounts for 78% of the total heat income, the higher post-combustion degree of the hearth gas, the more heat is generated. In the heat expenditure items, hot metal taken away accounted for 7.6%, slag taken away accounted for 3.5%, iron oxide reduction and coal and carbonate decomposition endothermic amount accounted for about 48%, gas away heat for 33.4%, and SRV furnace heat loss accounted for about 7%, which shows that in addition to reducing

Table 2 Heat balance calculation of Chinese HIsmelt plant

Serial no.	Items	GJ/tHM	%	Serial no.	Items	GJ/tHM	%
1	Hot blast	3.4	14.8	1	Hot metal	1.7	7.6
2	Coal combustion	17.8	78.0	2	Slag	0.8	3.5
3	Hot ore	1.3	5.8	3	Off-gas	7.6	33.4
4	Coal and fluxes	0.1	0.5	4	Dust	0.1	0.4
5	Slag forming heat	0.2	1.0	5	Endothermic reactions	11.0	48.1
				6	Heat loss	1.6	6.9
	Total	22.8	100.0		Total	22.8	100.0

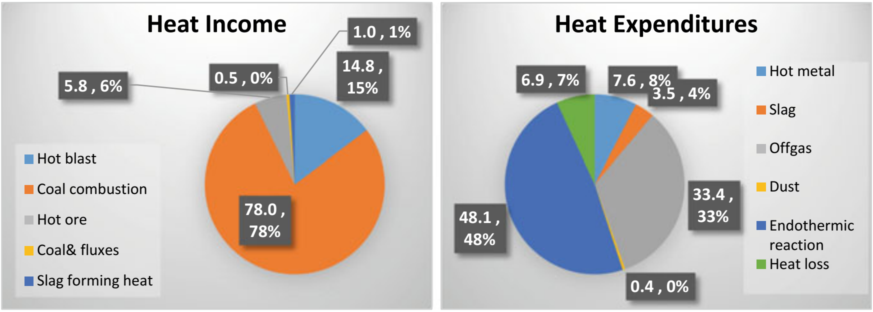

Fig. 2 Energy balances calculation of SRV

heat consumption, SRV exhaust took too much heat; this is mainly because the off-gas of the SRV temperature is very high, and at 1450 °C above, the off-gas volume of per ton hot metal is about 2240 Nm^3/tHM, so how to further improve the heat transfer efficiency in the furnace, reduce the heat brought out by off-gas per ton hot metal and to achieve higher energy recovery efficiency of waste heat of SRV off-gas, it is a key point to improving the energy utilization efficiency of HIsmelt process.

SRV Heat Transfer Process Analysis

The Heat Transfer Efficiency of the Fountains in SRV

The heat of the SRV mainly comes from the high-temperature flame zone which is generated by oxygen-enriched hot blast of HAB and hearth gas combustion; its heat transfer is divided into three parts: (1) heat transfer to the bath, (2) heat to the gas and ash, and (3) heat to the side cooling wall. Among them, the heat transfer to the coal gas and ash is about 7.7 GJ/tHM, the heat transfer to the sidewall is 1.6 GJ/tHM, the heat transfer to the slag iron is 13.5 GJ/tHM, and the effective thermal efficiency is only 59.2%.

The Factors Affecting SRV Fountain Heat Transfer Efficiency

The SRV heat transfer from the post-combustion high-temperature zone to molten slag and iron includes three ways: radiation, conduction, and convection. These three kinds of heat transfer methods must be considered when the slag layer forms the fountain. The formation of slag fountain area gives the primary and post-combustion heat and fountain flow a good heat transfer conditions in SRV; the falling droplets get the heat and merge with the rising droplet. And there is a balance transfer process through conduction and convection. After the droplets return to the slag layer, remix the pulverized coal which was just injected into the fountain, accepting the new heat transfer so the cycle repeats.

The main factors affect the heat transfer efficiency in bath include:

(1) The contact surface area between the high-temperature air flow and the fountain flow generated by the primary and post-combustion

The contact surface area of hot blast flow and fountain flow depends on the lances height, injection angle, injection pressure, slag viscosity, etc., which the slag viscosity may be the critical factor affecting the fountains forming effect. The greater the slag viscosity, the smaller the depth of the fountain penetrating high-temperature airflow, the larger the diameter of slag droplets in the fountain flow, and the worse the dispersion and uniformity in the off-gas, thus affecting the convective heat transfer effect. In addition, the contact area between the high-temperature airflow and the slag surface is affected by the distance between the lance and the slag face. The different heights of the lance position will directly affect the heat transfer and the effect of post-combustion.

(2) Temperature gradient between high-temperature air flow and slag droplet in fountains

The temperature gradient between the high-temperature airflow and the droplet can be improved by increasing the post-combustion degree, hot air temperature, and oxygen enrichment rate. The post-combustion degree has a great relationship with the high-temperature gas recirculation ratio; the lower the cycle ratio, the higher the oxygen potential in the airflow and the higher the post-combustion degree; the higher the cycle ratio, the lower the combustible gas concentration and the lower the post-combustion degree. The high-temperature airflow recirculation ratio is related to the furnace size H/D (the height from the outlet to bath/furnace diameter) and the lance height, as well as the reasonable position distribution between the lance inlet and the flue gas outlet.

(3) Reduce the sensible heat taken away by off-gas

The sensible heat of off-gas depends on the volume and temperature. The off-gas quantity reduction focuses on reducing the N_2 content and reducing the SRV off-gas temperature to improve heat transfer.

(4) Reduce the heat taken away by cooling water

The radiation heat transfer from high-temperature combustion zone to the furnace wall should be effectively controlled. On the one hand, to strengthen the fountain effect and increase the radiation to the slag, thereby inhibiting the radiation to the furnace wall. On the other hand, the cooling panel should form a stable and reasonable thickness of the slag layer, which can reduce the heat conduction of the furnace wall significantly.

The Influence of SRV Heat Transfer on Reduction Reaction

The slag layer and fountain in SRV is a multiphase reaction system with gas, liquid, and solid coexistence. After the iron ore powder injects in the iron bath, iron oxides will be reduced by carbon or CO in the slag to produce hot metal. The hot metal and non-molten carbon contact with the upper zone O_2 and CO_2 by the fountain action and are reoxidized; this process is called “reverse reaction”. In order to ensure that the reduction reaction can be carried out smoothly, and at the same time, it is better to inhibit the occurrence of the inverse reaction, the droplet should have a certain degree of particle size, which is a pair of contradictions with heat transfer to the droplet size requirements. Controlled the particle size distribution of the molten droplets is a crucial operation to achieve the optimal equilibrium of the heat transfer and reduction reaction.

Energy Efficiency Optimization of the HIsmelt Plant in China

In order to further improve the energy efficiency, the processes have been optimized in the design and construction process on the basis of the Kwinana practice, which includes the lance position control, the iron ore powder preheating system, the gas purification, and the waste heat utilization. And these have been practical applied in China HIsmelt factory.

Optimization of Lance Position Control for HAB

The structure, position control, and swirl characteristic of the HAB are very important to control the degree of inverse reaction in the SRV and improve the heat transfer efficiency in the molten bath. A relative lower position of the HAB is conducive to improving the heating strength, but an excessively low HAB position will cause an excessive reverse reaction, so the best position of the HAB can maximize the transmission of energy to the molten bath, and ensure that the reduction reaction can proceed normally. In order to improve the heat transfer efficiency in the SRV and adjust the lance position of the HAB, the HAB position design has been optimized in the design process of the HIsmelt plant in China.

The HAB position can be adjusted according to production requirements, by four 600 mm water-cooled spools. By adjusting the position of four water-cooled short tubes, the height gradient of HAB can be adjusted to 0, 0.6, and 1.2 m, which can provide more control means to ensure the working state of the HAB (Fig. 3).

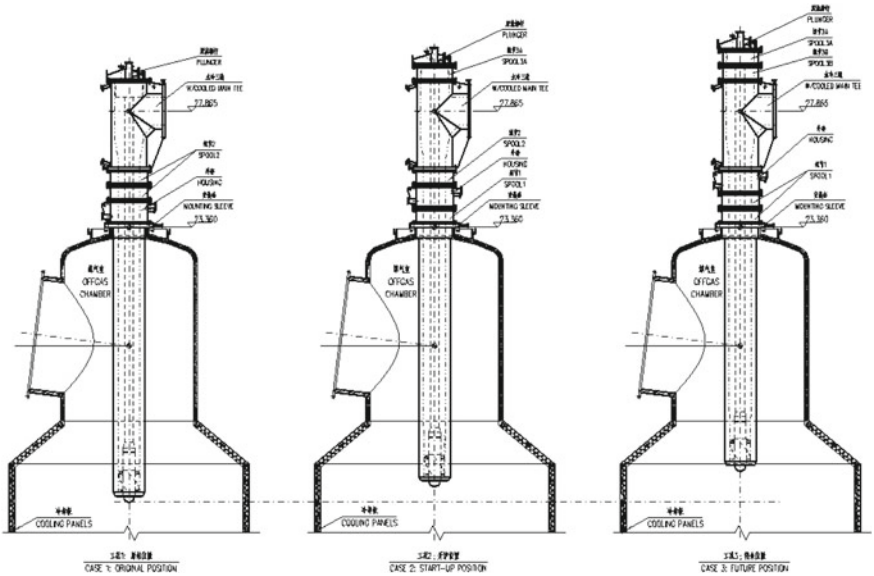

Fig. 3 Position adjustment schematic of HAB

Optimization of Off-Gas Waste Heat Utilization

Wet dedusting process is used for SRV off-gas scrubbing in Kwinana plant, in which the high-temperature gas enters the water-cooled hood, the temperature dropped to 800–1000 °C, and then dedusted and cooled through the ring seam scrubbing tower. After that, the gas temperature is dropped to below 100 °C, and the off-gas dust content is below 10 mg/Nm^3; then after further cooling, quality of the gas can meet the requirements of the following procedure. The above dedusting process can meet the dust content requirements of the gas, but the disadvantage is that the physical heat of the gas below 1000 °C cannot be recycled.

In order to achieve efficient utilization of waste heat and purification of SRV off-gas, the new process is adopted in the Chinese plant (see Fig. 4). The SRV off-gas with temperature of 1450–1650 °C is cooled firstly through the water-cooled hood down to 800–1000 °C, and then enters the cyclone to catch large particle dust, so that the dust content of the gas decreases to 20 g/Nm3. The gas temperature drops to 200–250 °C in waste heat boiler, and then the gas is further dedusted and cooled by ring seam scrubbing tower. The highest production of middle pressure steam is about 56 t/h (5.4 MPa). By adopting the above process, the utilization efficiency of the waste heat of SRV off-gas can be remarkably improved.

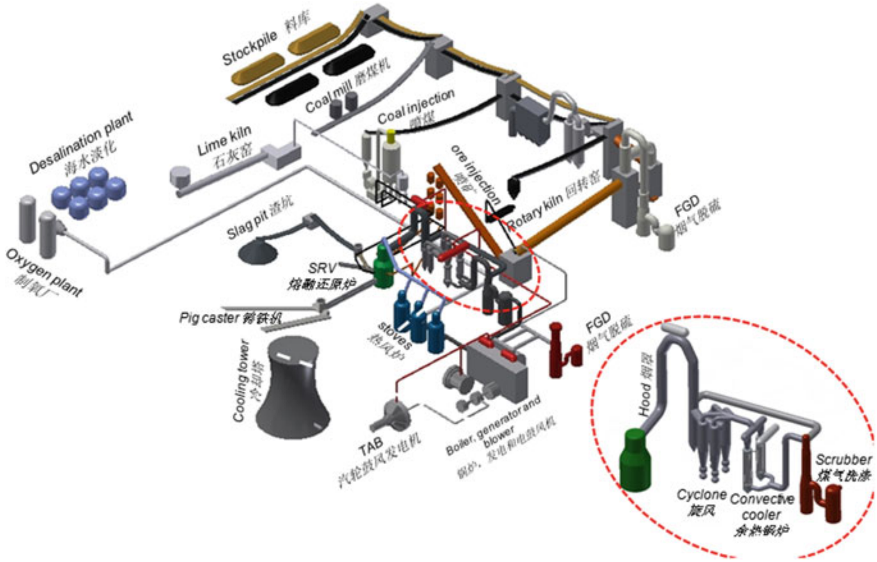

Fig. 4 SRV off-gas purification and energy recovery process

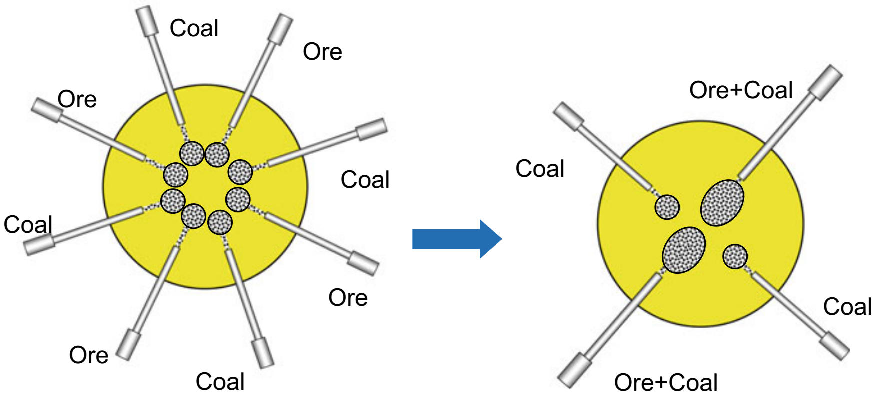

Fig. 5 Schematic of SRV ore + coal injection

Optimization of Solid Lance Arrangement

The design philosophy of multi points and small lances of ore and coal injection is used in SRV of Kwinana plant. The purpose is, through multipoint injection, to realize a uniform distribution of iron slag and solid material in the hearth, which helps to improve the kinetic condition of hearth reaction. There are four coal injection lances and four ore injection lances, which are located above hearth refractory and evenly alternately distributed along the circumferential direction (Fig. 5).

It has been proved by the research and production practice that the size range control ability of the slag and iron droplet can be further improved by reducing the number of lances and increasing the injection capacity of single mega lance, which can meet the need of heat transfer and reduction reaction and the requirement of the active furnace cylinder and the ore-coal injection amount. During the design process of the new plant, the design scheme of solid injection lances is simplified by reducing the lances from 8 to 4, which can realize the coal and ore mixed injection, simplify the solid injection system, reduce the equipment failure potential, and further improve the SRV production efficiency.

Conclusions

(1) The Chinese HIsmelt plant has been completed and put into operation in August 2016. At present, the plant operation is stable. Compared with the blast furnace process, the HIsmelt technology has significant advantages in the raw material flexibility, environmental protection, production cost, and so on, which has a bright development perspective.
(2) The SRV off-gas takes up about 33.4% of the total heat income, further improving the heat transfer efficiency and efficient utilization of the SRV off-gas is the key to improve the energy utilization efficiency of the HIsmelt process.
(3) The effective heat transfer efficiency in the SRV furnace is 59.2%, which is affected by the contact surface area in gas–liquid two-phase flow, temperature gradient, and the high-temperature gas quantity.
(4) In order to further improve the energy efficiency of the HIsmelt plant, the process improvement and optimization of the HIsmelt plant in China are carried out in the position control of HAB, ore powder preheating, gas purification, and waste heat utilization.

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