Energy Materials 2017

Conference Proceedings

Edited by:
Xingbo Liu
Zhengdong Liu
Kyle Brinkman
Subodh Das
Sebastien Dryepondt
Jeffrey W. Fergus
Zhancheng Guo
Minfang Han
Jeffrey A. Hawk
Teruhisa Horita
Peter Hosemann
Jian Li
Elsa Olivetti
Amit Pandey
Raul B. Rebak
Indranil Roy
Chengjia Shang
Ji Zhang

TMS
Springer

The Minerals, Metals & Materials Series

Xingbo Liu · Zhengdong Liu
Kyle Brinkman · Subodh Das
Sebastien Dryepondt · Jeffrey W. Fergus
Zhancheng Guo · Minfang Han
Jeffrey A. Hawk · Teruhisa Horita
Peter Hosemann · Jian Li
Elsa Olivetti · Amit Pandey
Raul B. Rebak · Indranil Roy
Chengjia Shang · Ji Zhang
Editors

Energy Materials 2017

TMS

Springer

Editors
Xingbo Liu
West Virginia University
Morgantown, WV
USA

Zhengdong Liu
China Iron and Steel Research Institute Group
Beijing
China

Kyle Brinkman
Clemson University
Clemson, SC
USA

Subodh Das
Phinix, LLC
Lexington, KY
USA

Sebastien Dryepondt
Oak Ridge National Laboratory
Oak Ridge, TN
USA

Jeffrey W. Fergus
Auburn University
Auburn, AL
USA

Zhancheng Guo
University of Science and Technology of China
Beijing
China

Minfang Han
Tsinghua University
Beijing
China

Jeffrey A. Hawk
U.S. Department of Energy
Albany, OR
USA

Teruhisa Horita
National Institute of Advanced Industrial Science
and Technology (AIST)
Tsukuba, Ibarakai
Japan

Peter Hosemann
University of California, Berkeley
Berkeley, CA
USA

Jian Li
CanmetMATERIALS
Hamilton, ON
Canada

Elsa Olivetti
Massachusetts Institute of Technology
Cambridge, MA
USA

Amit Pandey
LG Fuel Cell Systems Inc.
North Canton, OH
USA

Raul B. Rebak
GE Global Research
Schenectady, NY
USA

Indranil Roy
Schlumberger
Houston, TX
USA

Chengjia Shang
University of Science and Technology Beijing
Beijing
China

Ji Zhang
China Iron and Steel Research Institute Group
Beijing
China

ISSN 2367-1181 ISSN 2367-1696 (electronic)
The Minerals, Metals & Materials Series
ISBN 978-3-319-51647-9 ISBN 978-3-319-52333-0 (eBook)
DOI 10.1007/978-3-319-52333-0
TMS owns copyright; Springer has full publishing rights

Library of Congress Control Number: 2016963644

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Energy production is inherently a materials problem. Materials innovator Matthew Boulton and his team were as responsible for modern energy production as was the inventor of the steam engine itself, James Watt. Boulton and his team developed the metals and fabrication processes that made Watt's engine commercially viable for any number of applications, marketing the innovation under the Boulton & Watt company name, revolutionizing energy production and industry in the process.

More than 225 years later, we face new challenges wrought from the combustion of the same fossil fuels that first powered the industrial revolution, especially climate change resulting in large part from carbon dioxide emissions. Commitments by the United States and China—two of the world's largest CO_2 emitters—to reduce carbon dioxide emissions call for advanced energy systems that cry out for advanced materials. New materials and materials methods to enhance efficiency in the use of traditional fossil fuels, the safety of nuclear, and the affordability and practicality of renewable resources will form the foundation upon which next generation energy production systems will be built. Revolutionizing the way electricity is generated and transportation is driven remains inherently a materials problem. Scientists and engineers in the United States and China are leading today's materials innovation revolution.

That is why in 2014 US-based The Minerals, Metals & Metals Society (TMS) with its long-standing, international membership dedicated to minerals, metals, and materials and the 92,000-member Chinese Society for Metals (CSM) together launched the Energy Materials Conference. The first conference was held in Xi'an, a fitting locale, the ancient Chinese imperial capital and eastern-most point of the Silk Road where East met West 2200 years ago, a crossroad for the trade of materials and ideas. Energy Materials 2014 featured invited talks by world-leading energy materials experts as well as contributed presentations from the global minerals, metals, and materials community highlighting materials research and industrial innovations for both established and emerging energy systems and technologies.

Energy Materials 2017, the second in the series, draws from the success of that first conference and the worldwide draw of TMS2017, the 146th annual meeting &

exhibit of the world's foremost gathering of materials scientists and engineers, held in San Diego, California. This proceedings volume includes 40 papers from seven symposia covering energy and environmental issues in materials manufacturing and processing, materials in clean power, materials for coal-based power, materials for energy conversion with an emphasis on solid oxide fuel cells, materials for gas turbines, materials for nuclear energy, and materials for oil and gas.

These proceedings present recent advances in materials manufacturing and processing that incorporate methods and materials that are themselves environmentally sound. These proceedings also include discussions on the advancements in materials technologies to enable clean coal technologies, carbon capture, concentrated solar power, biomass fuels, and hydrogen-based power systems. Also presented are discussions about functional ceramic materials that will play an essential role in the commercialization of advanced fossil fuel conversion systems such as solid oxide fuel cells. Materials innovation within gas turbine technology particularly related to gas-fueled power plants is covered. Discussions about nanostructured and advanced materials revolutionizing oil and gas exploration and production in extreme conditions are presented as are discussions about the materials issues associated with improvements in nuclear energy.

These collected works demonstrates that—given the right materials—all energy sources have the potential to meet the world's growing demand for next generation, clean, affordable energy.

Xingbo Liu
Zhengdong Liu
Lead Editors

Contents

Part I Energy and Environmental Issues in Materials Manufacturing and Processing: Opportunities in the Steel Industry

Part II Energy and Environmental Issues in Materials Manufacturing and Processing: Opportunities in Aluminum Production, Waste Heat and Water Recovery

Part III Materials for Coal-Based Power: Materials For Coal-Based Power: Session I

Part IV Materials for Coal-Based Power: Materials for Coal-Based Power: Session II

Part V Materials for Coal-Based Power: Materials for Coal-Based Power: Session III

Part VI Materials for Coal-Based Power: Poster Session

Part VII Materials for Gas Turbines: Coatings

Part VIII Materials for Gas Turbines: Hot Corrosion and New Materials

Part IX Materials for Gas Turbines: Microstructure and Processing

Part X Materials for Gas Turbines: Poster Session

Part XI Materials for Nuclear Energy: Materials for Nuclear Applications I

Part XII Materials for Nuclear Energy: Materials for Nuclear Applications II

Part XIII Materials for Nuclear Energy: Environmental Effects

Part XIV Materials for Nuclear Energy: Accident Tolerant Fuels & Irradiation Effects

Part XV Materials for Oil and Gas and AMREE Oil & Gas III

About the Editors

Xingbo Liu is Professor and Associate Chair for Research in Mechanical & Aerospace Engineering Department at West Virginia University. He is internationally renowned for his research on materials in energy conversion and storage, especially for high temperature alloys and electrochemical energy systems such as solid oxide fuel cells and batteries. During his career, Dr. Liu has received numerous prestigious awards. In 2010, Liu received the Early Career Faculty Fellow Award from The Minerals, Metals & Materials Society (TMS). In 2011, he received an R&D 100 award for inventing an electroplated Mn-Co coating for solid oxide fuel cell interconnects. In 2013, Liu was named Innovator of the Year by TechConnect WV. In 2015, Dr. Liu was elected as Fellow of ASM International "for his significant contribution on R&D of high temperature materials for energy production and conversion, including superalloys in advanced power systems and solid oxide fuel cells". In 2016, he received the Brimacombe Medal from TMS "For significant contribution on research and development of high temperature materials and coatings for energy conversion, and extensive service to TMS". Dr. Liu has extensively served TMS and other professional societies. From 2011 to 2013, he served as the chair of the TMS High Temperature Alloys Committee, chair of the TMS Energy Conversion & Storage Committee from 2012 to 2014, and TMS Functional Materials Division (FMD) programming committee representative (2016–). He is the chair for the American Ceramics Society (ACerS) Basic Science Division (2016–2017) and an executive committee member of the

Electrochemical Society (ECS) High Temperature Materials Division. He has been the lead organizer and co-organizer of more than 20 international conferences and symposiums, including serving as the co-chair for the 8th (2014) and chair of the 9th (2018) Superalloys 718 & Derivatives Conferences. Dr. Xingbo Liu (TMS) and Dr. Zhengdong Liu (Chinese Society for Metals—CSM) have been serving as co-chairs for the Energy Materials 2014 and Energy Materials 2017 conferences, jointly organized by TMS and CSM.

Dr. Xingbo Liu has published more than 80 peer-reviewed journal papers and given numerous invited talks in the international conferences. He also holds three granted and four pending patents in the areas of batteries and electrochemical devices. He received his training in materials science and engineering from the University of Science & Technology Beijing, completing his Ph.D. in 1999.

Zhengdong Liu earned a B.A.Sc. degree (1985–1990) in Mechanical Engineering from Tsinghua University, China; a M.A.Sc. degree (1990–1993) in Materials Science from Central Iron and Steel Research Institute (CISRI), China; and a Ph.D. degree in Metallurgical Engineering from the University of British Columbia (UBC), Canada. Dr. Liu has served as Deputy Director, Professor and senior engineer at the Institute for Structural Materials, Central Iron and Steel Research Institute (CISRI) since 2002. CISRI is the biggest and the most important specialty steel and alloy research facility in China.

Dr. Liu has served as the leader of nationally integrated research and development group on advanced boiler steels and alloys used for 600 °C ultra super critical (USC) power plants in China since 2003. He has also served as the vice-chairman of the National Technical Committee for 700 °C A-USC Fossil Power Plants in China and the head of Materials Sub-Committee, National Technical Committee for 700 °C A-USC Fossil Power Plants in China since 2010; authored and co-authored more than 300 technical papers, holds 26 issued materials patents and 11 issued computer software copyrights, and authored and co-authored seven published technical books.

Kyle Brinkman is Associate Professor in the Department of Materials Science and Engineering at Clemson University in Clemson, South Carolina. He received his Ph.D. in Materials Science and Engineering from the Swiss Federal Institute of Lausanne in Switzerland (EPFL), obtained an M.S. in Materials Science and Engineering and a B.S. degree in Chemical Engineering from Clemson University. He recently joined Clemson in 2014 from the DOE's Savannah River National Laboratory (SRNL) where he was a principal engineer in the Science and Technology and served as the program manager for SRNL's Energy Efficiency and Renewable Energy Programs (EERE) from 2012–2014. Prior to working at SRNL, Kyle was a fellow of the Japanese Society for the Promotion of Science working at the National Advanced Institute of Science and Technology (AIST) in Tsukuba, Japan from 2005–2007.

Dr. Brinkman has authored or co-authored over 80 peer-reviewed technical publications and government reports. He was the recipient of the Karl Schwartzwalder Professional Achievement in Ceramic Engineering (PACE) from the American Ceramic Society in 2015, The Minerals, Metals & Materials Society (TMS) Young Leaders International Scholar Award in 2015, the U.S. Department of Energy, Fuel Cycle Research and Development Early Career Researcher Award in 2013, and the SRNL Laboratory Director's Early Career Exceptional Achievement Award in 2011. He serves as the Material Advantage (MA) and Keramos faculty advisor for Clemson's undergraduate students in materials science and engineering.

Dr. Brinkman's current research is in the area of energy materials including ceramic materials for electrochemical gas separation and processing, structure/property relations in solid oxide fuel cell systems, and radiation tolerant crystalline ceramics for applications in nuclear energy.

Subodh Das CEO, Phinix, LLC, is a globally recognized and respected inventor, researcher, commercializer, analyst, thought leader, expert, and consultant to the light metals (aluminum, magnesium and titanium) industry specializing in the areas of technology, recycling, manufacturing, carbon and energy management and new product and process developments. He is a prolific writer of papers and books and frequent invited presenter at international conferences and an active blogger.

Sebastien Dryepondt

Jeffrey W. Fergus is Professor of Materials Engineering and Associate Dean for program assessment and graduate studies in the Samuel Ginn College of Engineering at Auburn University. He received a B.S. in metallurgical engineering from the University of Illinois in 1985 and a Ph.D. in Materials Science and Engineering from the University of Pennsylvania in 1990. He had a postdoctoral appointment at the University of Notre Dame before joining Auburn University in 1992. His research interests lie in materials for high temperature and electrochemical applications. This includes the development of chemical sensors for gases, such as carbon dioxide and water vapor, and constituents in molten metals, such as dissolved gases and alloying elements. He has also worked on materials for energy conversion and storage applications, including batteries, fuel cells, thermoelectric generators and gas turbine engines. Dr. Fergus has been involved in volunteer activities with The Minerals, Metals & Materials Society (TMS) including service on the Board of Directors as Director of Professional Development.

Zhancheng Guo the Director and Professor of State Key Lab. of Advanced Metallurgy (USTB), received his Ph.D. in Chemical Engineering from Chinese Academy of Sciences in 1992. His recent research interest is advanced technology for ironmaking processing, environmental engineering in ironmaking and steelmaking. He is the member of editor committees of the Journal of Iron and Steel Research International, and Chemical Industry and Engineering (China).

Minfang Han

Jeffrey A. Hawk is Task Technical Coordinator of the Advanced Alloy Development Project. The project works to improve existing and develop new heat-resistant alloys for combustion technologies. Dr. Hawk attended the University of Virginia, obtaining degrees in Civil Engineering (B.S.) and Materials Science (M.S. and Ph.D.). Subsequently, Dr. Hawk worked at the University of Virginia as a senior scientist developing heat-resistant dispersion strengthened aluminum alloys before accepting a position at the University of Alabama as Assistant Professor. Dr. Hawk then moved to Albany, Oregon, to become a manager of the Fracture and Wear Group at the Bureau of Mines and then division chief of the Wear and Corrosion Division of the Albany Research Center when it was transferred to the Department of Energy (DOE). Dr. Hawk left DOE in 2005 to become a senior engineer at General Electric Co., working in the Low Temperature Materials Development Group within the GE Power Generation Group, in Schenectady, NY in support of the design and manufacture of large steam turbines. In 2009 Dr. Hawk returned to National Energy Technology Laboratory (NETL) at the DOE as a materials research engineer.

Teruhisa Horita is the principal senior manager, Research Institute of Energy Conservation, at National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan. He received a B.A. of Science in 1990, M.A. of Engineering in 1992, and Ph.D. in 1998, all from Waseda University, Tokyo, Japan. In 1992 he joined AIST as a research scientist. Dr. Horita's research focuses on materials for solid oxide fuel cells (SOFCs) and electrochemistry for SOFC reaction. He has developed the special technique of the combination of electrochemical method and secondary ion mass spectrometry (SIMS). He has published more than 70 scientific research papers were published as a first author and more than 200 papers as a co-author.

Dr. Horita has received numerous awards including the Richard M. Fulrath Award, The American Ceramic Society, for the contribution to the fundamental studies of Solid Oxide Fuel Cells in 2005; the Ornzio DeNora Foundation Prize on Electrochemical Energy Conversion, International Society of Electrochemistry (ISE) in 2001; and the Excellent Papers award of the Electrochemical Society of Japan in 1994.

Peter Hosemann is Associate Professor in the Department for Nuclear Engineering at the University of California Berkeley and current Vice Chair of the department. Professor Hosemann received his Ph.D. in Materials Science from the Montanuniversitaet Leoben, Austria in 2008 while performing research as both a student and a postdoc (carried out at Los Alamos National Laboratory) on lead-bismuth eutectic (LBE) corrosion, ion irradiations and microscale testing. Professor Hosemann joined the faculty at Berkeley in 2010 and has authored more than 95 peer-reviewed publications since 2008. In 2015 he won the The Minerals, Metals & Materials Society (TMS) Early Career Faculty Fellow Award and the AIME Robert Lansing Hardy Award. His current research interest is in radiation damage of metals and ceramics, corrosion of materials in liquid metal cooled systems as well as additive manufacturing.

Jian Li is a senior research scientist at CanmetMATERIALS in Natural Resources Canada. He obtained his B.Sc. in Mechanical Engineering from Beijing Polytechnique University; M.Sc. in Metallurgical Engineering from Technical University of Nova Scotia (TUNS) and Ph.D. in Materials and Metallurgical Engineering from Queen's University, Kingston, Ontario. Dr. Li has broad experience in materials processing and characterization including alloys deformation, recrystallization and micro-texture development. He has extensive experience in focused ion beam (FIB) microscopy, and an expert in various aspects of scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS) and electron probe micro-analyzer (EPMA) analyses. Dr. Li holds a patent, has authored three book chapters, and has published more than 120 papers in scientific journals and conference proceedings.

Elsa Olivetti is the Thomas Lord Assistant Professor in the Department of Materials Science and Engineering at Massachusetts Institute of Technology (MIT). She received her B.S. in Engineering Science from the University of Virginia and her Ph.D. in Materials Science from MIT working on development of nanocomposite electrodes for lithium-ion rechargeable batteries. Olivetti joined MIT's faculty in 2014 where her current research focuses on improving the environmental and economic sustainability of materials in the context of rapid-expanding global demand. Olivetti leverages machine learning as well as data mining coupled with engineering and macroeconomic models to determine the scaled impact of novel materials and processes.

Amit Pandey is the development leader of the group that supports the reliability of fuel cell components and stack at LG Fuel Cell Systems (2013–). In addition, Dr. Pandey is project leader for material selection for high temperature ceramics and alloys for product development. He started his professional career as a postdoctoral fellow at the Johns Hopkins University (2010–2011) and later moved to Oak Ridge National Laboratory (2011–2013). He received his Ph.D. (2010) from the University of Maryland in Mechanical Engineering, M.S. (2005) from University of Arizona and B-Tech (2003) from Indian Institute of Technology (IIT) Varanasi, India. Dr. Pandey is an active member of material societies (The Minerals, Metals & Materials Society—TMS, ASM International, American Ceramic Society—ACerS) and committees related to energy conversion and storage. He has also received young professional and leaderships awards from these societies.

Raul B. Rebak is a senior corrosion engineer working at the GE Global Research Center in Schenectady, New York since October 2007. Dr. Rebak earned a Ph.D. degree in materials science and corrosion from The Ohio State University (USA). Previously, he was employed at the University of California Lawrence Livermore National Laboratory where he was the lead for materials corrosion testing for the Yucca Mountain Project. Dr. Rebak has more than 30 years' experience in corrosion science and corrosion engineering both from the academic and the industrial fields, and has an extensive research background in nuclear materials, including power generation and nuclear waste disposition. Currently he leads a multimillion dollars' multi-year project with the Department of Energy in Accident Tolerant Nuclear Fuels. Dr. Rebak is also involved in several other areas of materials degradation such as oil and gas, aviation, transportation, and energy storage. He is very active in seven national and international professional societies chairing committee activities, organizing symposia and publishing. Dr. Rebak is a Fellow of NACE International, The Corrosion Society.

Indranil Roy a former University of California Regents Fellow, Indranil Roy pursued his Ph.D. on mechanical properties and origin of corrosion resistance of bulk nanocrystalline materials on a National Science Foundation (NSF), Nanoscale Interdisciplinary Research Team (NIRT) program on mechanical behavior of bulk nanostructured materials. Dr. Roy started with Schlumberger Technology Corporation in the fall of 2006 with Reservoir Evaluations. Since then he has worked in several different technology groups from Downhole Testing, Enabling Technologies to Infinity Product Line. Dr. Roy is currently the project manager, nanomaterials under the Multi Stage Stimulation (hydraulic fracturing) umbrella with a focus on water reactive materials technology. He has spearheaded materials development for the oil and gas industry's first fully degradable plug and Perf system—Schlumberger's Infinity. His main focus has been developing innovative solutions for oil and gas in the mechanical, materials and corrosion domains. His research encompasses understanding interactions of stressed alloys including nanomaterials deployed in corrosive downhole environments (rich in acid gases) at high pressures and temperatures (HPHT). His efforts also includes introduction and usage of nanostructured materials for HPHT sour service. Dr. Roy has been involved in the ultrafine grained materials group at The Minerals, Metals & Materials Society (TMS) and has organized several symposia including "Advance Materials and Reservoir Engineering for Extreme Oil and Gas Environments" organized bi-annually since 2013. He also serves as the vice chair of the TMS subcommittee for the Offshore Technology Conference (OTC) since 2014 and has organized many panels and technical sessions at OTC on behalf of TMS. Dr. Roy has served as a key reviewer for several journals, *Materials Science and Engineering A*, *Metallurgical and Materials Transactions A*, *Corrosion*, etc. Dr. Roy has authored several publications/proceedings and delivered numerous invited talks and seminars. He has over 50 U.S. and international patents/patent applications on some of his key findings on nanocrystalline materials and HPHT phase behavior of supercritical reservoir fluids.

Chengjia Shang is Professor at the University of Science and Technology Beijing (USTB), chief scientist at the State Collaborative Innovation Center of Advanced Steel and Technology, and the secretary general of the Materials Science Branch of the Chinese Society for Metals. For many years Prof. Shang has been dedicating himself into the research, development and application of high performance microalloyed steel, including the fields as follow: physical metallurgy for Nb bearing structural steel, microstructure design and control for high performance steel, and development of offshore platform, ship building, high-rising building, high performance bridge, and high grade pipeline steels. He has been managing and participating several national funded research projects. He has numerous experiences in collaboration with steel industries to develop high performance steel. He received second-place for the National Science and Technology Progress Award; three first-place, two second-place, and one third-place honor of the Provincial and Ministerial Science and Technology Progress Awards, and the Charles Hatchett Award from the Institute of Materials Minerals and Mining (IOMMM) in 2011. He has published approximately 150 academic papers, and participated in the composing of four academic writings, and was invited many times to conferences to present plenary lectures, keynotes, and invited speeches.

Ji Zhang

Part I

Energy and Environmental Issues in Materials Manufacturing and Processing: Opportunities in the Steel Industry

Waste Energy Recovery Technology of Iron and Steel Industry in China

Xu Zhang, Hao Bai, Juxian Hao and Zhancheng Guo

Abstract In China, many technologies have been applied to improve the energy efficiency of the processes. Among these technologies, the waste energy recovery technology, for example, CDQ (coke dry quenching), CCPP (combined cycle power plant), waste energy recovery from Linz-Donawitz process, etc. have been used widely and contributed a lot to the energy savings whose application status and energy recovery effect assessment were analyzed in this paper. Further, the technologies of the next generation, aiming to recover the low-grade waste heat, are under development considering the exergy efficiency principle with novel energy conversion methods. Two typical processes under development which are the vertical tank cooling system for sinter sensible heat recovery and the Organic Rankine Cycle (ORC) system to recover the waste heat from blast furnace (BF) slag quenching water for power generation were introduced and their significance and the feasibility were analyzed.

Keywords Waste heat recovery · Energy consumption · Sinter sensible heat · Vertical tank · Organic rankine cycle

Introduction

The total energy consumption of the iron and steel industry accounts for about 26% of industrial energy consumption in China, with the highest proportion of energy consumption in all the industries [1]. Thus, much attention has been paid to the waste energy resource which accounts for more than 60% of the total energy input

---

X. Zhang · H. Bai (✉) · J. Hao · Z. Guo
State Key Laboratory of Advanced Metallurgy, University of Science
and Technology Beijing, 30# Xueyuan Road, Beijing 100083, China
e-mail: baihao@metall.ustb.edu.cn

X. Zhang · H. Bai · J. Hao
School of Metallurgical and Ecological Engineering, University of Science
and Technology Beijing, 30# Xueyuan Road, Beijing 100083, China

X. Liu et al. (eds.), *Energy Materials 2017*, The Minerals, Metals
& Materials Series, DOI 10.1007/978-3-319-52333-0_1

in iron and steel industry [2]. The general methods and application fields of waste energy recovery in domestic industries are shown in Fig. 1.

The waste heat resource can be divided as follows according to the temperature: high temperature waste heat (above 650 °C), medium temperature waste heat (230–650 °C) and low temperature waste heat (below 230 °C), which are 3.36, 2.19 and 2.89 GJ/t steel respectively, equivalent to 287 kgce/t steel totally [3, 4]. In general, it is easier to recover the waste heat in high and medium temperature section, which can be used as the materials preheating, civil heating or directly driving a steam turbine or gas turbine to generate electricity. However, the low temperature waste heat which accounts for above 30% usually cannot recover efficiently; therefore, the waste heat resources in low temperature section have increasingly become the focus of potential application.

In this paper, the 5 current China's existing key and mainstream technologies of waste heat or energy were investigated in aspects of application status and energy recovery effect. Two representative technologies, vertical tank cooling system to recover the sinter sensible heat and the Organic Rankine Cycle (ORC) system to recover the waste heat from blast furnace slag quenching water were introduced, and the significance and feasibility were analyzed.

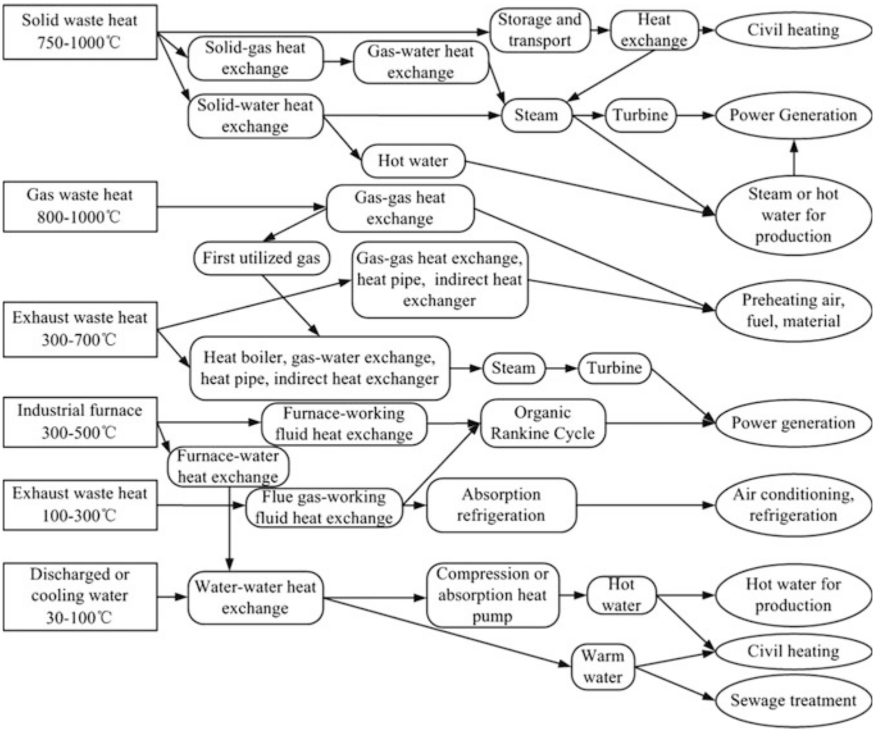

Fig. 1 The general methods and application fields of waste energy recovery in domestic industries

Waste Energy Recovery Technologies

Coke Dry Quenching (CDQ)

In the system of coke dry quenching (CDQ), the hot coke is cooled in the coke tank by the cold inert gas, which is heated to be about 650 °C which will be the energy source in the waste heat boiler to generate steam for power generation. The cooled inert gas then is blown into the coke tank again by a circulating fan. The process is shown in Fig. 2.

CDQ is an excellent technology to recover the sensible heat of the hot coke which would be wasted if wet quenching technology is used. About 80% hot coke sensible heat, which accounts 35–40% of the energy consumption of coke oven, can be recovered about 1.35 GJ heat per ton coke [5]. To some extent, environmental pollution can be reduced as a result of avoiding the use of coal to produce the same amount of electricity generated by CDQ system. Another advantage of CDQ is that the quality of coke increases, for example, the crushing strength (M40) will increase by 3–5%, abrasive resistance will be improved by 0.2–0.5% (M10), along with a lower CRI and a 5% higher CSR [6, 7].

However, there are still some technical problems and defects which are needed to be improved for CDQ technology in China. For example, the refractory is easy to be damaged, the operation is complicated and the subsequent environmental problems are caused [7].

In 1985, the CDQ system was put into production in Baosteel, which marked the technology of CDQ was firstly introduced to China. In 2003, the first domestic self-designed CDQ system was put into operation in Ma'anshan Steel Corporation

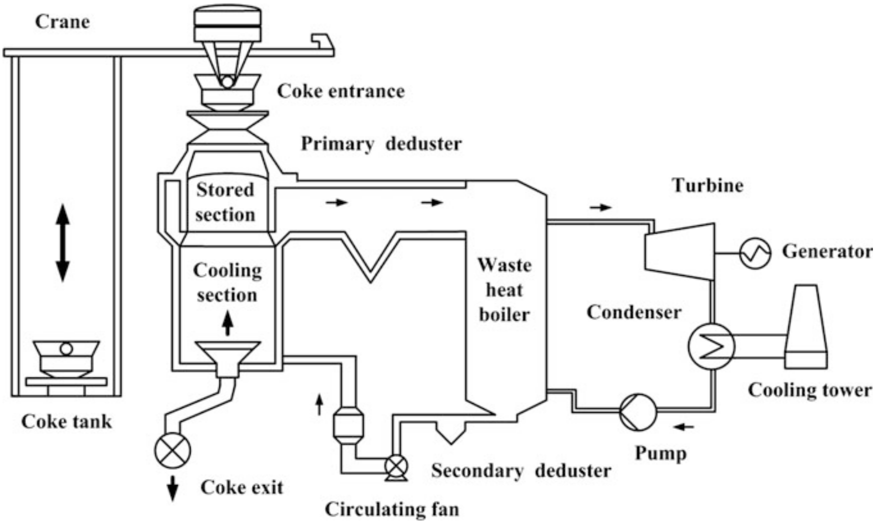

Fig. 2 Schematic process of CDQ

Table 1 The application of CDQ in China

Year	2005	2010	2011	2012	2013	2014
CDQ/sets	21	105	113	136	155	178

(Masteel). By 2014, the number of CDQ systems has increased by 70% during the past four years (Table 1). In this sense, China owns the most CDQ systems throughout the world [8].

Blast Furnace Top Gas Recovery Turbine Unit (TRT)

Blast furnace top gas recovery turbine unit (TRT) is a set of energy recovery equipment which makes use of the surplus pressure of the BFG (blast furnace gas) on the top of the blast furnace which keeps 0.12–0.25 MPa (gauge pressure) to promote the turbo expander and generate electricity. Compared with other conventional thermal power generation and waste heat recovery system, there is extreme low cost of electricity and nearly no pollution during operation. The process is shown in Fig. 3.

According to statistics, the electricity generation will be 20–40 kWh per ton iron if the TRT system is working well. In 2013, the domestic pig iron production is 660 million tons, and penetration rate of TRT is 98%, according to the capacity of generation 30 kWh per ton iron, the amount of TRT power recovery is 19.6 billion kWh, equivalent to the amount of power generation of a power plant whose capacity is 2.5 million kW a year [9].

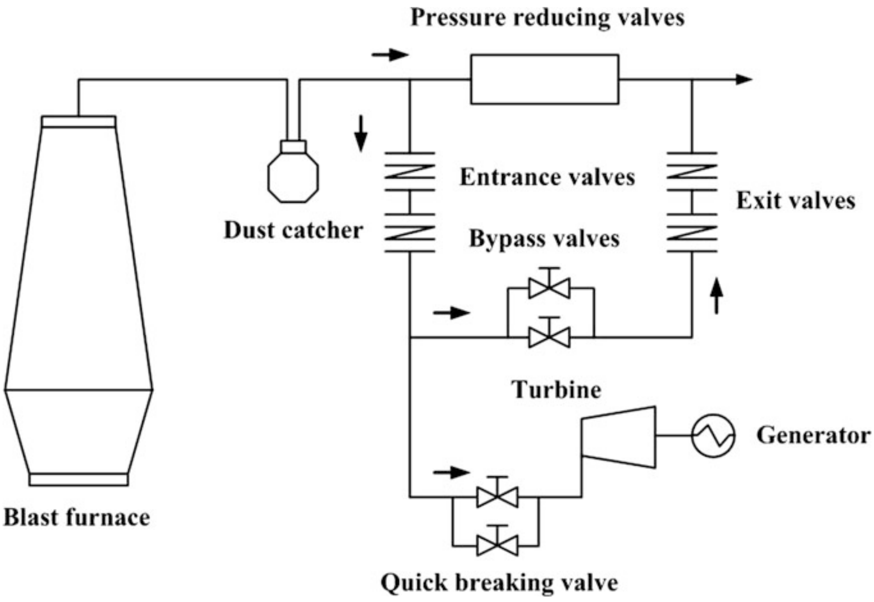

Fig. 3 Schematic process of TRT

Problems and defects that exist in the TRT application in China: (1) the ratio of dry TRT systems, especially in the large blast furnace, is relatively low; (2) the improper selection of TRT system will cause an insufficient amount of gas while entering the TRT device; (3) owing to the existence of a great amount of blast furnaces that smaller than 1000 m^3, recovery efficiency and economic feasibility will be restricted by the low top pressure.

In China, the TRT technology was introduced in late 1970s and applied in the 1980s firstly. By 2007, the number of TRT sets reached more than 400, and for all the 56 blast furnaces of 2000 m^3 were equipped with TRT and 95% of those of 1000 m^3 were equipped with TRT [9]. According to the statistics of China Iron and Steel Association, there had been a total of more than 600 blast furnaces equipped with 597 sets of TRT by the end of 2010 in China.

Power Generation from Sintering Waste Heat

The sinter sensible heat accounts for up to 35% of the entire sintering process, a cooler machine is applied after the sintering machine to recover this part of the waste heat [10].

In general, the sinter is cooled by air blowing on a loop or belt cooler. The cold air blowing from the bottom of the cooler is heated by the hot sinter bed and becomes exhaust gas, which can reach 350–400 °C in the first gas collecting hood and 250–300 °C in the second hood, both of which will be introduced into the waste heat boiler to generate steam for power generation [11]. The schematic process of sinter sensible heat power generation is shown in Fig. 4.

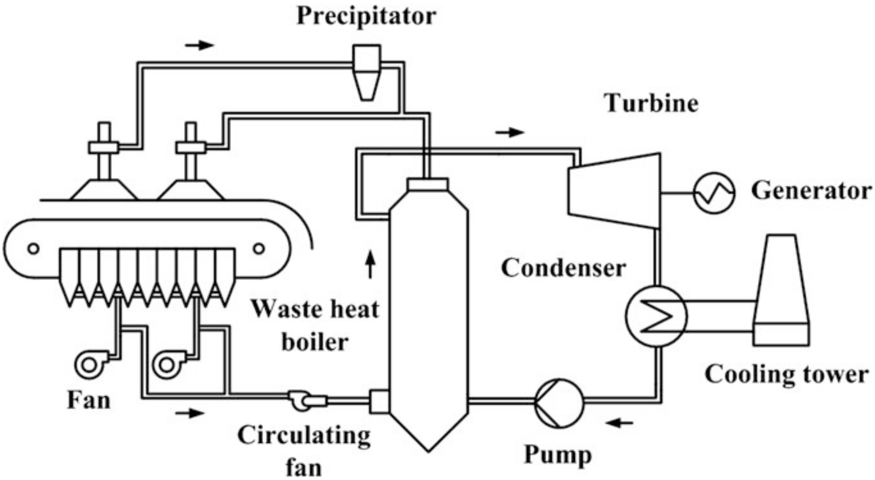

Fig. 4 Schematic of sinter sensible heat power generation process

The waste heat recovery system of sintering process has been applied in many steelmaking enterprises in China. For example, Jinan Steel Corporation of Shandong Province has brought in the technology in 2006. Anyang Steel Corporation of Henan Province has introduced a dual-pressure waste heat boiler for power generation in 2008. Ma'anshan and Wuhan Steel Corporation can achieve the capacity of 70 million and 0.285 billion kWh annually respectively [12].

Steelmaking Process Waste Heat Recovery

The physical heat carried by the converter gas, whose temperature is about 1450–1500 °C at the outlet of the converter and the amount of the heat it carries accounts for about 10% of the total energy consumption in the process, is valuable to recover [13].

In 1980s, the German OSCHATZ company successfully developed the electric furnace gas evaporative cooling system, and then it was applied to the converter gas cooling. For this cooling system, the high temperature gas is cooled by water and transforms into saturated steam in the evaporative cooling flue, during which the latent heat of cooling water can be recovered. The high pressure (2.5–3.2 MPa) steam then enters into the heat accumulator, after which the steam pressure drops to lower than 1 MPa and the temperature becomes 169–179 °C [13, 14]. The schematic process of steelmaking process waste heat recovery is shown in Fig. 5. This saturated steam can only be used in chemical production and civil heating with a low efficiency. In many circumstances, the saturated steam has to be exhausted because of its limited utilization, causing the waste of the recovered steam.

To solve these problems, the low-pressure saturated steam can be directly used to generate power, which can reduce the amount of purchased power and primary energy consumption of generation in iron and steel enterprises. Jinan Steel Corporation of Shandong Province was the first one who implemented the converter flue gas power generation system in 2007, and the electricity index has been

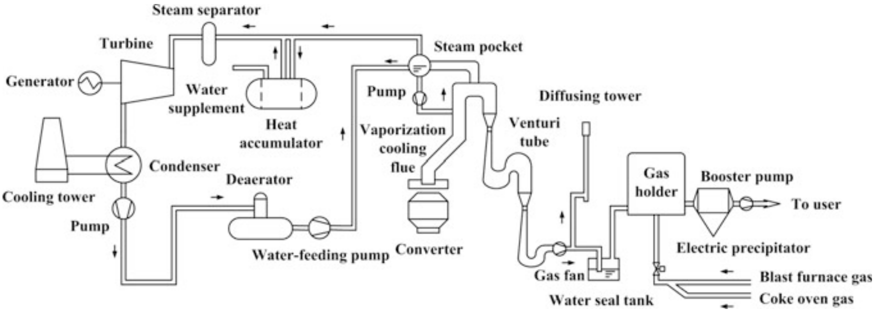

Fig. 5 Schematic of steelmaking process waste heat recovery

achieved up to 9.81 kWh/t steel by 2010. With the well developed technology of evaporative cooling flue manufacture, the heat of 800–1600 °C can be utilized efficiently, however, the under 800 °C part is not recovered completely resulted from the technical defects [15].

The converter gas, which is rich in carbon monoxide, is cleaned and recovered with the unburned method. Two typical systems are used widely in China, one is OG system, basically a wet dust removing technology involved, and LT system, a kind of dry dust removing technology with electrostatic precipitator. After cooling and cleaning process, the gas with the CO content of 50–70% is sent to users after storage, pressurization and transportation.

In 1980s, China's Baosteel introduced the OG system from Japan and the technology has been promoted gradually. In 21st century, the LT system has been applied widely in China. The amount of converter gas recovered has reached 70, 90–100 and 110–120 Nm^3/t steel in general, good and excellent level, respectively, considering the average calorific value as 8300 kJ/Nm^3 for the gas.

Combined Cycle Power Plant (CCPP)

Combined cycle power plant (CCPP) in steelmaking companies generally consists of a blast furnace gas supply system, gas turbine system, waste heat boiler system, steam turbine and generator system. The by-product gas, delivered from the steel pipe network of gases, is mixed with air after purified and pressurized, and then put into the combustion chamber to obtain the flue gas with high temperature (1000–1500 °C) and pressure (1.5–2.4 MPa), which is delivered into the gas turbine unit to expand and generate electricity. And the exhausted gas with lower temperature (500–600 °C) comes out of the gas turbine, enters into the waste heat boiler to produce steam, which get into the steam turbine to drive a generator set for power generation. Figure 6 shows the schematic process of CCPP.

CCPP is an advanced technology which makes full use of blast furnace by product gas and improves energy efficiency, whose thermoelectric conversion efficiency is up to 40–45% without the extra heat supplement. Compared with blast furnace gas power plant project, 1.68×10^6–2.16×10^6 MWh more amount of electricity will be generated by CCPP when the annual running time is calculated as 8000 h, which is a considerable benefit obviously [18].

The problems and defects existing in domestic CCPP: (1) the requirements of fuel quality are higher than the traditional process; (2) the quality of gas will be demanding strictly.

At present, the 145 MW CCPP in Baosteel is the largest one in domestic, which uses 100% blast furnace gas with the heat value 3266 kJ/m^3. The following production index will be achieved after beginning production: The output power is 145 MW, and steam supply is 180t/h, the thermoelectric conversion efficiency is 46.52% and annual generation capacity is 1.1 billion kWh [19].

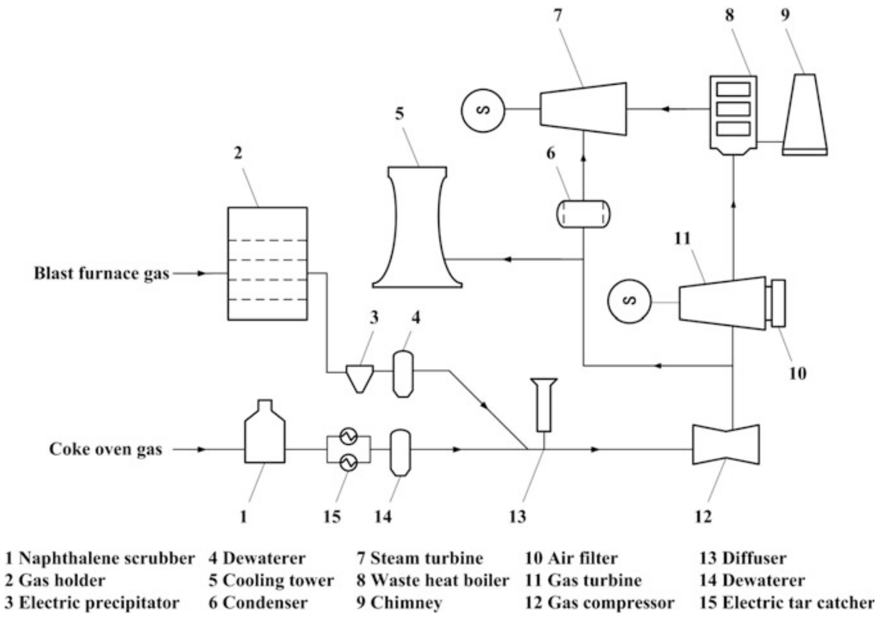

Fig. 6 Schematic process of CCPP

Brief Summary

Overall, the total amount of waste energy resources of China's iron and steel industry is 455.1 kgce/t steel, while the efficiency of recovery is only 45.6%, compared with the above 90% in the advanced foreign enterprises. At present, there are about more than 30% waste energy that cannot be recovered in domestic iron and steel industry, especially the key technologies for low temperature waste heat are not mature enough. Not only import of advanced foreign waste energy recovery technologies, but also self-dependent innovation can accelerate the China's pace of energy conservation and emission reduction.

The Advanced Waste Heat Recovery Technology

Vertical Tank Cooling System

The sintering waste heat is mainly recovered and utilized by the conventional process, the blast machine of belt-cooling or ring-cooling, in this kind of technology, the problem of high leakage rate in sintering system exists leading to the