12th International Symposium on High-Temperature Metallurgical Processing

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TMS

Springer

The Minerals, Metals & Materials Series

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Jerome P. Downey · Dean Gregurek · Baojun Zhao ·
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ISSN 2367-1181 ISSN 2367-1696 (electronic)
The Minerals, Metals & Materials Series
ISBN 978-3-030-92387-7 ISBN 978-3-030-92388-4 (eBook)
https://doi.org/10.1007/978-3-030-92388-4

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

Preface

This book presents selected papers submitted for the 12th International Symposium on High-Temperature Metallurgical Processing at The Minerals, Metals & Materials Society (TMS) Annual Meeting & Exhibition held in Anaheim, California, USA in 2022. The symposium created a platform for presenting ongoing research on the analysis, development, and/or operation of high-temperature processes that involved processing of mineral resources, production, and treatment of metals, alloys, ceramic materials, etc. It also provided a space for reporting fundamental and applied research related to metallurgical waste generation, characterization, minimization, collection, separation, treatment, and disposal. Moreover, it was open to people who are interested in integrating experiment and computation to solve enduring engineering problems due to the high complexity, high cost, and high energy consumption of metallurgical process and to those who work on improving practical metallurgical processes based on techno-economic and life cycle analyses for commercial-scale production, which identify how to enhance economic feasibility and minimize environmental impact. At the TMS 2022 Annual Meeting & Exhibition, this symposium received a total of 73 abstracts from authors from around the world, of which 68 submissions were accepted. After peer review, 58 papers were included in the book.

This book is expected to serve as a treasured reference for academia and industry covering a wide range of research fields. Educators, researchers, professionals, and students will enjoy the diversity of topics that reflect brilliant achievements of the authors on developing innovative and sustainable technologies and routes for minerals processing, physical metallurgy, process metallurgy, and materials science and processing.

The editors of this book would like to express their gratitude to the authors for their contribution and willingness to share their research findings and to the reviewers for their time and effort that ensured the quality and timeliness of the publication. The editors would also like to thank the Pyrometallurgy Committee and Extraction and Processing Division of TMS for sponsoring the symposium and Springer for publishing the book.

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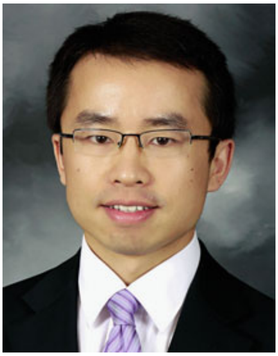
About the Editors



Zhiwei Peng is a professor in the School of Minerals Processing and Bioengineering at Central South University, China. He received his B.E. and M.S. degrees from Central South University in 2005 and 2008, respectively, and his Ph.D. degree in Materials Science and Engineering from Michigan Technological University, USA, in 2012. His research interests include dielectric characterization, ferrous metallurgy, microwave processing, comprehensive utilization of resources, waste valorization, powder agglomeration, low-carbon technology, process simulation, electromagnetic shielding, and synthesis of functional materials.

Dr. Peng has published over 170 papers, including more than 120 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*; *Waste Management*; *Metallurgical and Materials Transactions A*; *Metallurgical and Materials Transactions B*; *JOM*; *Journal of Power Sources*; *Fuel Processing Technology*; *Energy & Fuels*; *IEEE Transactions on Magnetics*; *IEEE Transactions on Instrumentation and Measurement*; *Ceramics International*; *Powder Technology*; and *Separation and Purification Technology*. He holds 56 Chinese patents and has served as an associate editor for *Mining, Metallurgy & Exploration*, as a guest editor for *JOM* and *Metals*, and as an editor for *PLOS ONE* and *Cogent Chemistry*. He has also been a member of editorial boards of *Scientific Reports*, *Journal of Central South*

University, and *Journal of Iron and Steel Research International*, and has served as a reviewer for more than 70 journals.

Dr. Peng is an active member of The Minerals, Metals & Materials Society (TMS). He has co-organized 10 TMS symposia and co-chaired 24 symposia sessions since 2012. He is a member of the Pyrometallurgy Committee and the vice chair of the Materials Characterization Committee. He was a winner of the TMS EPD Young Leaders Professional Development Award in 2014 and the TMS EPD Materials Characterization Award Best Paper—1st Place in 2020.

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Dr. Downey is presently the Goldcorp Professor of Extractive Metallurgy at Montana Tech where he serves as Department Head of Metallurgical and Materials Engineering as well as the Campus Director of the Montana University System Materials Science Ph.D. program. Dr. Downey's research efforts are currently focused on the study of fundamental properties of slags, molten salts, and glasses; vapor phase extraction and refining of rare earth elements; synthesis and sintering of non-oxide ceramic and composite materials; and applications of nanocomposite particles for water remediation.

Dean Gregurek is a senior mineralogist in the RHI Magnesita Technology Center, Leoben, Austria since 2001. Dr. Gregurek received his M.Sc. degree at the University of Graz in 1995 and his doctorate degree in Applied Mineralogy from the University of Leoben in 1999. Prior to RHI Magnesita, he worked for two years for Luzenac Europe in talc business. His current research interests and technical expertise are focused on chemical and mineralogical studies related to interactions between refractories, molten metals, and slags from pyrometallurgical furnaces. Dr. Gregurek has been a TMS member since 2012, *JOM* advisor (2014–2017), chair of the Pyrometallurgy Committee (2018–2020), and a co-organizer for the 7th–12th International Symposium on High-Temperature Metallurgical Processing (TMS Annual Meetings 2016–2021) and Furnace Tapping (TMS Annual Meeting 2022).

Baojun Zhao is a Professor in the College of Materials, Metallurgy and Chemistry at Jiangxi University of Science and Technology, Ganzhou, China. His primary fields of research are fundamental and applied investigations relevant to high-temperature processing of metals and materials. He has developed a series of novel research techniques to enable high-quality research to be carried out. A large number of experimental data on phase equilibrium and viscosity from his research directly supported industrial operations and development of thermodynamic and viscosity modeling. He has published over 200 refereed journal and conference papers and received several international awards to demonstrate his leading research achievements. He has long-term collaborations with many international companies on metallurgy and resources to support efficient utilization of low-grade minerals and optimization and development of pyrometallurgical processes.

Onuralp Yücel completed his technical education with a Ph.D. in Metallurgical Engineering from Istanbul Technical University (ITU) where he has held the post of Professor since 2002. He was a Visiting Scientist at Berlin Technical University between 1987 and 1988. He carried out postdoctoral studies at the New Mexico Institute of Mining and Technology, Socorro, USA between 1993 and 1994. Prof. Yücel has as many as 400 publications/presentations to his credit, which include topics like technological developments in the production of a wide range of metals, ferroalloys, advanced ceramic powders, and application of carbothermic and metallothermic processes, among others. He was the vice chairman of ITU, Metallurgical and Materials Engineering Department (MMED) between 2004 and 2007. He has been a director of ITU, Applied Research Center of Material Science & Production Technologies between 2006 and 2012. He was the chairman of ITU, MMED between 2016 and 2018.

Prof. Yücel is a member of the international advisory board of the International Symposium on Boron, Borides and Related Materials (ISBB), International Symposium on High-Temperature Metallurgical Processing organized by TMS, 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, ZnO), smelting and reduction of slags, production ferroalloys, alloys and metals carbothermic and metallothermic processes (SHS) in EAF or in ladle (Mg, Ca, Sr, Cu, Co, V, Cr, W, Zn, ferroboron, cobaltboron, nickelboron, ferronickel, nickel pig iron, ferrotungsten, ferromolybdenum, ferromanganese, silicomanganese, ferrovanadium, ferrochromium, iron-nickel-chromium-molybdenum, 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 aluminum dross, steel scale and EAF dust, Waelz slag, galvanizing ash, brass production wastes, and vanadium sludge produced aluminum production, and grit production from aluminum, copper, and steel slags.

Ender Keskinkilic earned his undergraduate degree in 1999 from the Department of Metallurgical and Materials Engineering of Middle East Technical University (METU), Ankara, Turkey. He continued his M.S. and Ph.D. studies in the same department and worked as a Research Assistant in 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, Dr. Keskinkilic moved to Eregli-Zonguldak in 2003 and worked in the Quality Metallurgy and RD Department of Eregli Iron and Steel Works Co. (ERDEMIR), which is the leading steel company in Turkey for the qualities produced and the production capacity. After earning his Ph.D. in 2007, he returned to university and to work in the Department of Metallurgical and Materials Engineering of Atilim University, Ankara, in 2008. Dr. Keskinkilic has been working as faculty in Atilim since 2008 and has been a full-time professor since 2020. His primary field of interest is extractive metallurgy and more specifically pyrometallurgical processes such as iron- and steelmaking, ladle metallurgy, ferroalloy production, and non-ferrous extractive metallurgy. He has been acting as the Chairperson of the Department of Metallurgical and Materials Engineering since July 2018 and as the Director of Graduate School of Natural and Applied Sciences since April 2021.

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 to the Department of Metallurgical Engineering, the University of Utah. Since 2003, Dr. Jiang has been a Professor in the School of Minerals Processing & Bioengineering at Central South University. He has been Specially Appointed Professor of Chang Jiang Scholar Program of China since 2008 and dean of the school since 2010.

His research interests include agglomeration and direct reduction of iron ores and extraction of refractory gold ores. He has undertaken more than 50 projects from the 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 is actively involved in the areas of utilization of non-traditional ferrous resources such as complex ores and various solid wastes. He has published 320 technical papers and 6 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 35 patents and has more than 30 conference presentations.

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Part I
Simulation of High-Temperature Processes

3D Experimental Model Study on Gas–Solid Flow of Raceway in BF

Cong Li, Qingguo Xue, Xing Peng, Haibin Zuo, Xuefeng She, Guang Wang, and Jingsong Wang

Abstract The transfer phenomenon and chemical reactions happening in raceway play a key role in both metallurgical principle and industrial operation of blast furnace (BF). Hot air with high blasting velocity resulting in efficient gas–solid motion, which determines the velocity field and furthermore temperature field, influences the total rate of chemical reaction. A 1/3rd scale 3D cold sector experimental model taking blast air kinetic energy as similarity criterion is built to study the gas–solid motion phenomenon by using 80–110 m/s gas inflow and real coke granule (average dimeter: 10–12 mm). The results indicate that, to study the movement inside of raceway, using the blast air kinetic energy as similarity criterion is much more reasonable than the Reynolds number or Froude number.

Keywords Raceway · Blast air kinetic energy · Cold experimentation · Gas–solid interaction

Introduction

In BF production, the transmission phenomenon and chemical reaction in raceway are very important and have always been the focus of research. For example, raceway in actual BF by microwave reflection method is directly measured [1]. Through the cold physical model, the different effects of two-dimensional slot model and three-dimensional sector model in whole furnace model are studied [2, 3]. The application of numerical simulation can comprehensively study the multiphase flow, temperature field, transmission phenomenon, composition distribution, and chemical reaction in BF [4, 5].

In the cold simulation of physical model, the commonly used coke particle substitutes are glass beads, plastic balls, beans, and grains. The density, equivalent diameter, and internal friction coefficient of these particles are very different from those of coke.

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Z. Peng et al. (eds.), *12th International Symposium on High-Temperature Metallurgical Processing*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-92388-4_1

Besides, the selected similarity criterion is generally Reynolds number or Froude number, and thus, the blast speed is low. There are some deficiencies in revealing the particle motion under the interaction of gas–solid, especially the high-speed motion [2, 6].

In this paper, using blast air kinetic energy as similarity criterion and coke as filler, a 1/3rd scale 3D sector physical model is established to simulate the gas–solid flow in the lower part of BF at four blast speeds of 80, 90, 100, and 110 m/s, with emphasis on the particle movement in the raceway. Experiments show that it is reasonable to use blast air kinetic energy as similarity criterion and coke as filler, which can more accurately reflect the actual situation in the raceway of BF tuyere and improve the reliability of physical cold simulation.

Model Description

Model Geometry

A cold sector model scale of 1/3rd was determined. The basic geometric dimensions of the model are as follows. The cold model is made of plexiglass, and measurement holes with an alignment of 10 × 10 cm are reserved on one side wall, as shown in Fig. 1 (Table 1).

Fig. 1 3D model experimental facility (empty and charged)

Table 1 Dimension of real industrial BF and model (unit: mm)

	Real industrial BF	Model
Hearth radius	2600	867
Hearth height[a]	2900	540
Bosh height	3000	1000
Belly radius	3000	1000
Belly height	1200	100
Tuyere diameter	100	35
Tuyere central line height	2500	400
Raceway depth[b]	998	350
Raceway height	865	300
Raceway width	563	200

[a] Hearth is shortened for the reason of no hot metal liquid
[b] Raceway parameter is calculated according to literature [7, 8]

Table 2 Blast air kinetic energy real industrial BF and model

	Real industrial BF	Model
Tuyere diameter (mm)	110	35
Real blast speed (m/s)	190	110
Mass flow (kg/s)	1.136[a]	0.1275
Blast air kinetic energy (kJ/s)[b]	20.495	0.771

[a] The effects of blast pressure and temperature are considered
[b] The ratio of is 26.58

Taking Blast Air Kinetic Energy as the Similarity Criterion

In this experiment, the blast air kinetic energy is used as the similarity criterion when determining the blast speed. The size of coke particles should also be one-third of the actual coke, so the mass of actual coke in industry is 27 times that of the coke particles used in this model. The blast air kinetic energy should also be reduced to one twenty seventh of actual BF (Table 2).

Particle Physical Properties and Measuring Devices

According to the real density and volume, six kinds of particles are selected: hollow alumina ball, coke (average diameter 12 mm), chickpea, black bean, red bean, and mung bean. The physical properties are shown in Table 3.

The density and average equivalent diameter of coke and chickpea are similar. Therefore, when filling the model, gray chickpea is used to replace some coke particles, which not only ensures the accuracy and reliability of physical simulation, rather

Table 3 Particle physical properties

	Real density (kg/m^3)	Average single particle mass (kg)	Average single particle volume (m^3)	Average equivalent diameter (m)
Alumina ball	2435	1.35E−03	5.56E−07	0.0102
Coke	1280	7.92E−04	6.19E−07	0.0106
Chickpea	1242	6.54E−04	5.26E−07	0.0100
Black bean	1163	2.10E−04	1.80E−07	0.0070
Red bean	1302	1.31E−04	1.01E−07	0.0058
Mung bean	1360	6.15E−05	4.52E−08	0.0044

than hollow alumina ball, chickpea, black bean, red bean, or mung bean, but also plays a role of tracing.

Use L-shaped pitot tube + digital display instrument and hot air velocimeter to measure the gas flow velocity in the model. Use a high-speed industrial camera to capture particle motion and obtain motion data, and the image storage interval is 25 ms.

Results and Discussion

Gas Superficial Velocity Distribution

After obtaining the velocity values in the horizontal and vertical directions, the contour map of gas flow superficial velocity distribution on the vertical plane passing through the tuyere central line is drawn, as shown below (Figs. 2, 3, 4, 5, 6, 7, 8 and 9).

It can be seen from the contour map that after the core air flow enters the model from the tuyere, because the space expands instantaneously, the kinetic energy decays rapidly, and the velocity gradient is large. The core air flow quickly decays from high speed to 25–40 m/s differently. When approaching the end wall, the horizontal speed further decays to 3–7 m/s differently. Finally, subject to the obstruction of the end wall, the core air flow turns to the vertical direction.

Motion of Single Particle Under the Interaction of Gas–Solid

Through a pipe above the tuyere, a single particle of six kinds is put into airflow. A horizontal section is set when making the pipeline, so as to avoid friction and gravity to the greatest extent. Record the horizontal position of particles between two contiguous pictures (the scale plate in the image below is 5 × 5 cm), and the

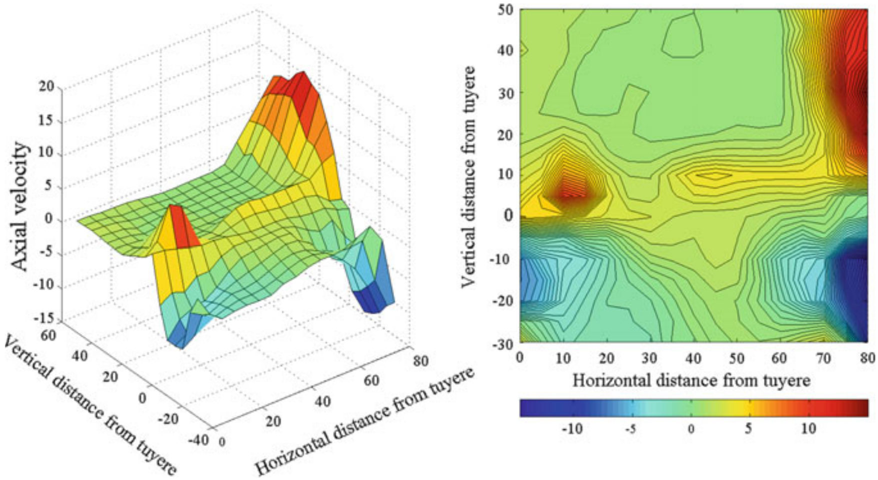

Fig. 2 Contour of axial velocity in plane *XY* through tuyere central line (blast speed: 80 m/s, *X* and *Y* axes unit: cm)

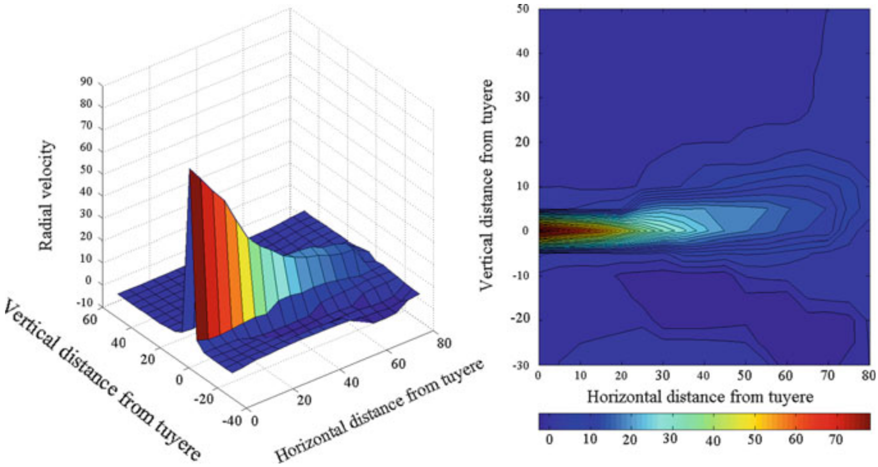

Fig. 3 Contour of radial velocity in plane *XY* through tuyere central line (blast speed: 80 m/s, *X* and *Y* axes unit: cm)

storage interval of two contiguous pictures is 25 ms, so as to obtain the particle movement speed (Fig. 10).

The moving speed of particles is measured for many times, and the average value is taken to obtain the results, as shown below (Fig. 11).

It can be seen from the above figure that with the increase of blast speed, the particle movement speed increases obviously, and the movement speed of particles with low density and small equivalent diameter, such as mung bean and red bean,

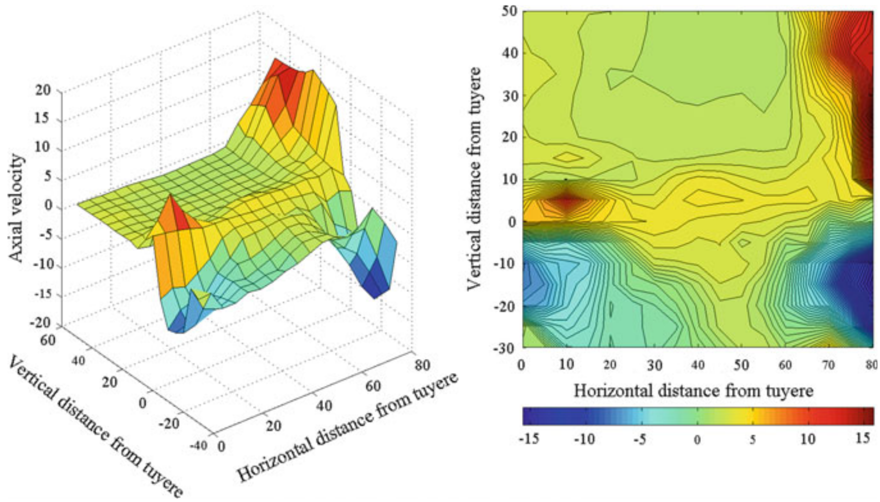

Fig. 4 Contour of axial velocity in plane *XY* through tuyere central line (blast speed: 90 m/s, *X* and *Y* axes unit: cm)

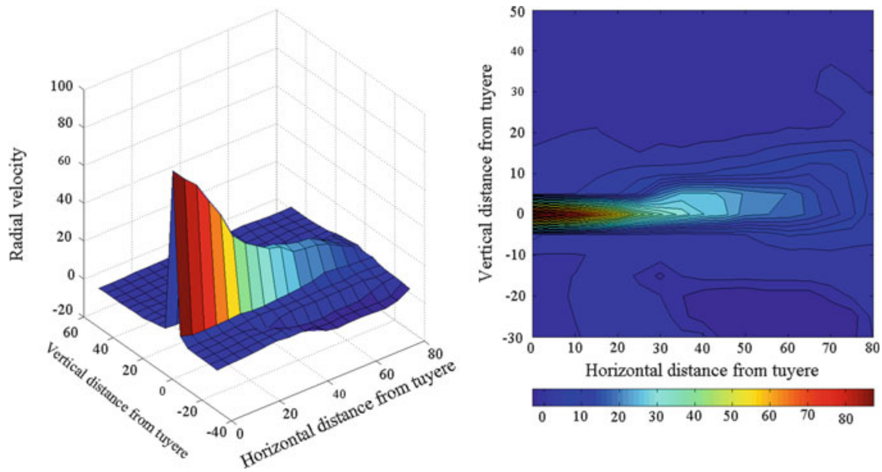

Fig. 5 Contour of radial velocity in plane *XY* through tuyere central line (blast speed: 90 m/s, *X* and *Y* axes unit: cm)

increases more obviously. This is consistent with the sharp increase of the specific surface area of powdered charge (≤5 to 8 mm) and the easy fluidization of powdered particles.

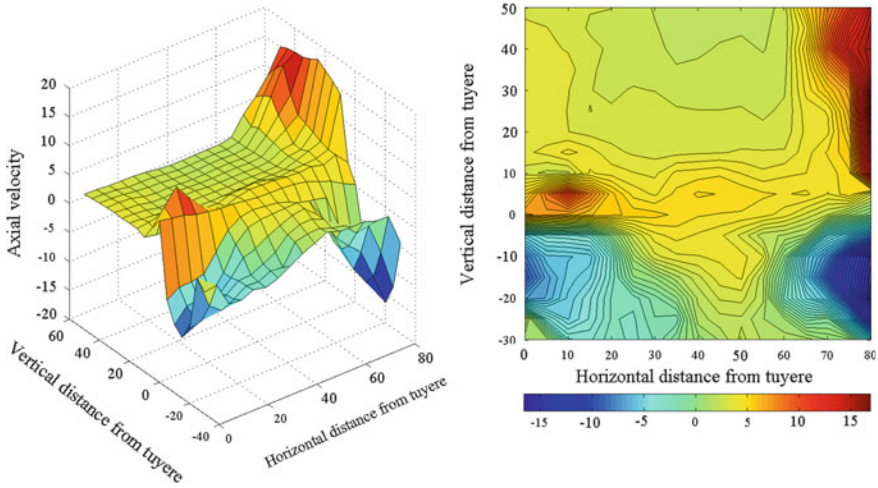

Fig. 6 Contour of axial velocity in plane *XY* through tuyere central line (blast speed: 100 m/s, *X* and *Y* axes unit: cm)

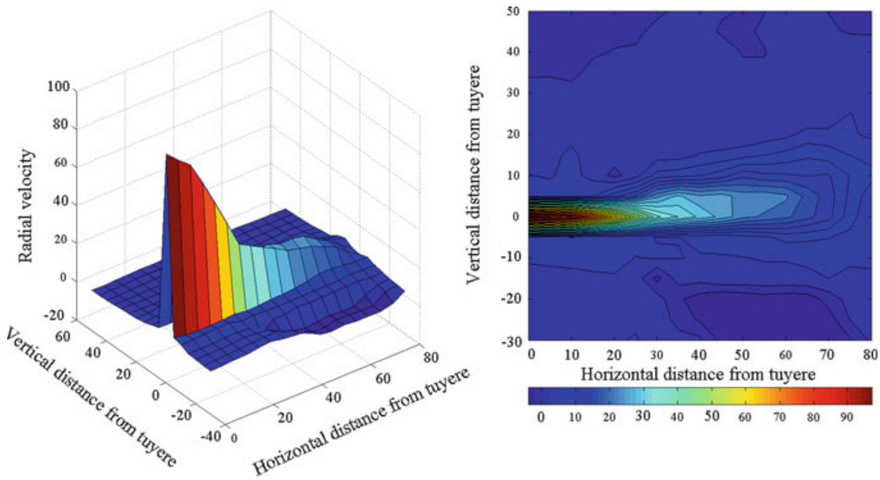

Fig. 7 Contour of radial velocity in plane *XY* through tuyere central line (blast speed: 100 m/s, *X* and *Y* axes unit: cm)

Multi-particle Motion Under Gas–Solid Interaction

Multi-particle motion experiments were carried out under four blast speeds: 80, 90, 100, 110 m/s. Three kinds of particles: alumina ball, chickpea, and coke are put into it (Fig. 12).

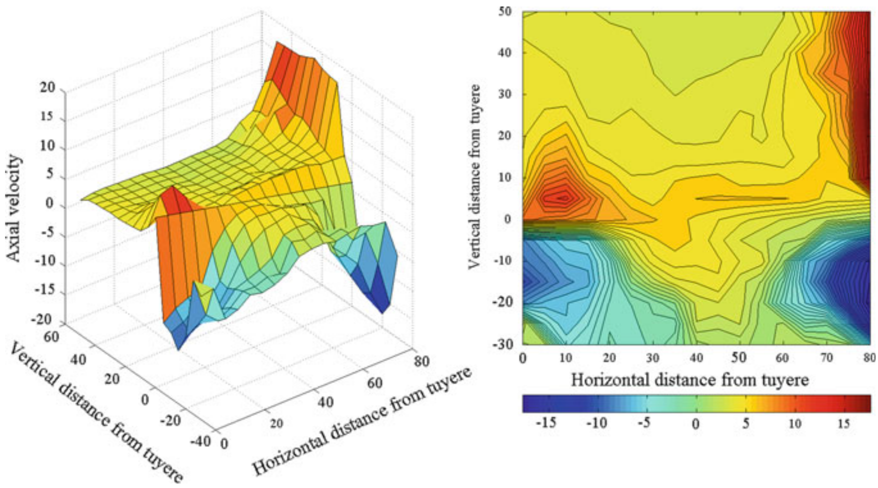

Fig. 8 Contour of axial velocity in plane *XY* through tuyere central line (blast speed: 110 m/s, *X* and *Y* axes unit: cm)

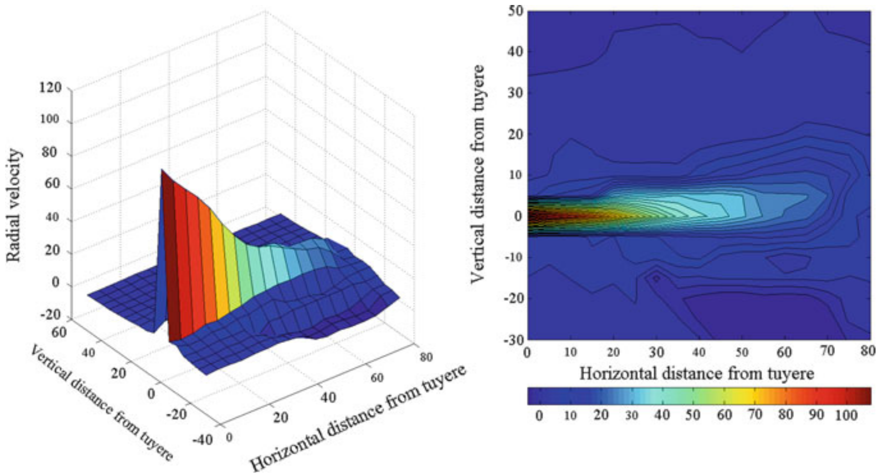

Fig. 9 Contour of radial velocity in plane *XY* through tuyere central line (blast speed: 110 m/s, *X* and *Y* axes unit: cm)

After obtaining the position information, similar to the motion of a single particle, the motion speed of particle can be calculated, as shown in Table 4.

Because of the elastic collision force between particles, the velocity of most coke particles is lower than that of single particles. At 100 m/s and 110 m/s, there are more moving particles, and the particle velocity decreases significantly. The frequency of particle at 100 m/s entering in the middle low-speed region is more than 110 m/s (Fig. 13).

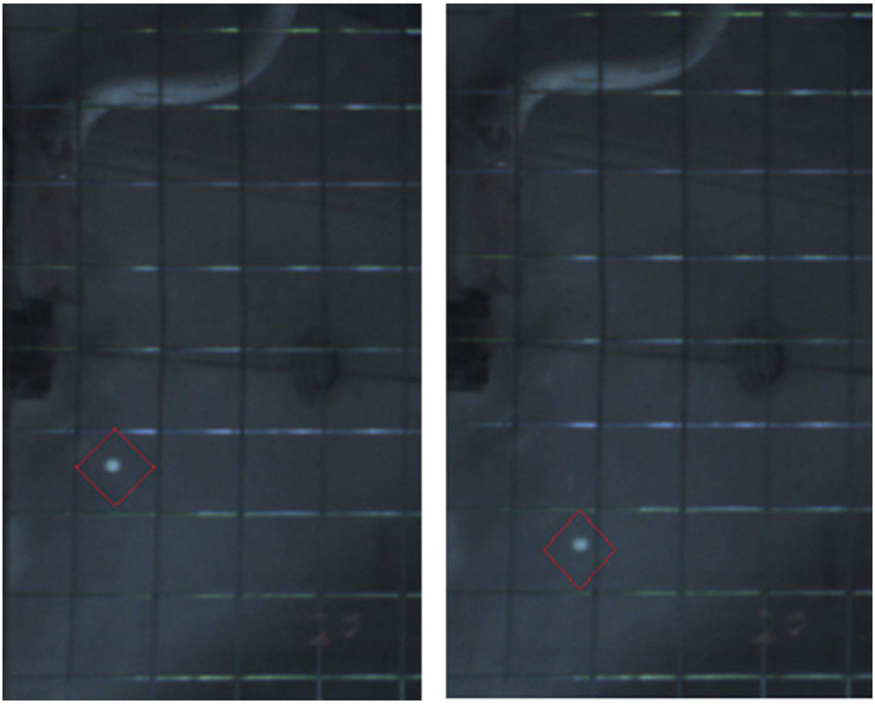

Fig. 10 Two contiguous images of alumina ball at 80 m/s blast speed

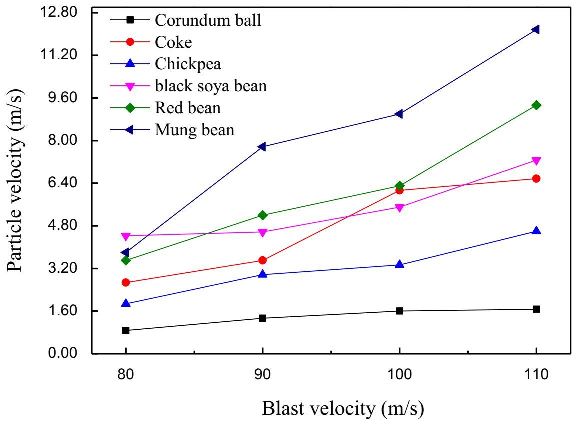

Fig. 11 Particle velocity under different blast speeds

According to the particle velocity and direction, the raceway can be divided into four regions: the lower rightward region, the upper leftward region, the right upward region, and the middle low-speed region.