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Clean and highly-efficient utilization of coal

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The International Symposium on Coal Combustion (ISCC-9) was held at the Qingdao City, China in July, 21–24, 2019. It attracted over 270 engineers and scientists from 16 countries including China, USA, Germany, Japan, Russia, Australia, South Korea, India, South Africa, Turkey, Pakistan, Italy, Colombia, Vietnam, Portugal, and Switzerland. The symposium has strongly reinforced the collaboration and discussion between academic researchers and industry experts, which emphasizes the main theme of the ISCC of establishing an effective bridge between academia and industry. The first ISCC was inaugurated at Tsinghua University, Beijing, China in 1987 under the consistent support of many distinguished scientists/engineers including Prof. Junkai Feng, Prof. Xuchang Xu, Prof. Douglas Smoot, Dr. Ernest L. Daman, Prof. Adel Sarofim, Prof. Klaus Hein, Prof. Ulrich Renz, Prof. Lothar Reh, Prof. Masayoshi Sadakata, Prof. Keiji Makino, and Prof. Jianxiong Mao, etc. Since then, the ISCC has been proudly hosted by Tsinghua University for over three decades, once every four years, as a non-profit platform to promote research and development in the field of science and technology of solid fuel combustion, gasification, and the controls of pollutants and CO₂ emissions.

The main goal of this special column is to present a set of most recent studies with original scientific contributions to clean and highly-efficient utilization of coal. In this special column, 12 of 175 papers that are more coherent to our theme are carefully selected by two-round reviewing. These remarkable accomplishments are surely to benefit coal utilization and stimulate new ideas worldwide.

Key contributions to this special column:

Cai et al. studied the combustion characteristic of blended coal including lignite and bituminous coal. The different ratios and air-staged combustion experiments are conducted in a drop tube furnace. The combustion characteristic, reductive gases CO and H₂, and pollutants of NO_x and H₂S are studied. Through the air-staged combustion experiments which conducted in an electric heated down-fired furnace (DFF), the relationship between NO_x and H₂S reduction with CO generation in the fuel-rich zone is identified. Based on this observation, a modeling strategy is proposed: instead of CH_i which is difficult to calculate, the CO concentration is used to quantify NO and H₂S homogeneous reduction.

Zhang et al. studied the Lu'an bituminous chars and ashes prepared by pyrolysis and combustion processes under N₂ and air atmospheres respectively. Scanning electron microscope (SEM) indicates that the number density and physical dimension of the ash spheres exuded from the char particles both gradually increase as the pyrolysis temperature rise, thus the coalescence of ash spheres can be obviously observed above 1100°C. When the pyrolysis temperature increases to 1300°C, some flocculent materials appear on the char particle surface. It can be speculated that β-Si₃N₄ is generated during the pyrolysis process in N₂ with the help of energy dispersive spectrometer.

Liu et al. focused on a circulating fluidized bed (CFB) combustor burning Zhundong (ZD) lignite; the effect of oil shale semi-coke (SC) addition on the ash deposit mineralogy and morphology was studied in a laboratory-scale CFB. 10% and 20% semi-coke of high aluminosilicate was respectively added to ZD lignite and the blend was then combusted in the CFB furnace at 950°C. The mineralogy, morphology, chemistry and size distributions of the deposited ash on both windward and leeward of the probes at the flue path was systematically characterized. When

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SC is added into ZD, the agglomerates between ash particles decreases, and more coarse-grained discrete particles appear, indicating a decrease in deposit viscosity and the fouling propensity.

Yang et al. conducted the study on ignition of single coal particles under low oxygen concentrations ($X_{O_2} < 21\%$) using a tube furnace. The surface temperature (T_s) and center temperature (T_c) of the coal particles were obtained from the images taken by an infrared camera and thermocouples respectively. The results indicate the responses of T_s and T_c to the variation of X_{O_2} is different: T_s decreases while T_c keeps nearly constant with increasing X_{O_2} at a low level. In addition, the ignition delay time is less sensitive to the furnace temperature while T_i is more sensitive to T_w at a low X_{O_2} than in air. At a low X_{O_2} , buoyancy plays a more significant role in sweeping away the released volatiles during the ignition process.

Alam et al. reviewed the ash content, composition and melting characteristic of ashes in differently ranked coal and biomass, and the slag formation mechanism, characteristics and structure were discussed. In addition, the available methodologies and formulae for slag viscosity measurement/prediction are reviewed and the current limitations and potential applications are summarized. Discussions on the slagging behaviour of the different ranks of coal and biomass by reviewing the viscosity measurement methods, viscosity prediction models and factors that affect the slag viscosity are carried out. This review also show that the existing viscosity models and slagging indices can only predict the viscosity and slagging propensity of high-rank coals satisfactorily.

Yan and Chen et al. studied the gas/particle flow characteristics in a novel swirling pulverized coal burner of a 29 MW pulverized-coal industrial boiler. The results indicate that the mean axial velocity and the particle volume flux in the central region of the burner outlet are negative, which indicates that the central recirculation zone is formed. In the central recirculation zone, the absolute value of the mean axial velocity and the particle volume flux increase when the external secondary air volume increases. However, the size of the central reflux zone is basically unchanged when varying the air volume ratio.

Yan and Sun et al. studied the effects of blend ratio on combustion and pollution emission characteristics for co-combustion of Shenmu pyrolyzed semi-char (SC) and Shenhua bituminous coal (SB) in a 0.35 MW pilot-scale pulverized coal furnace. Gas temperature and concentrations of gaseous species (O_2 , CO, CO_2 , NO_x and HCN) were measured in the primary combustion zone under different blend ratios. It is found that the stand-off distance of ignition changes monotonically from 132 to 384 mm with the increase of pyrolyzed semi-char blend ratio. Effects on the combustion characteristics may be neglected when blend ratio is less than 30%. Above 30% blend ratio, the increase of blend ratio postpones ignition in the primary stage and lowers burnout rate.

Liu et al. studied the Huangling bituminous coal with different sizes in a drop-tube furnace at 1273, 1473 and 1673 K under air atmosphere. The SEM and cross-section analysis were used to study the physical properties of the collected ash cenospheres and the effects of combustion parameters on the ash film fraction. The results show that the ash film fraction exceeds 0.85 at high temperature, which indicates the majority of ash is distributed at char burnout stage. The ash film fraction increases with increased temperature and carbon conversion ratio, while it decreases when the coal particles have a large size. The high fraction of ash film provides a reasonable explanation for the extinction event at the late burnout stage.

Yang et al. investigated the fuel combustion characteristic under O_2/N_2 and O_2/CO_2 atmospheres at fluidized bed combustion conditions, and a one-dimensional single particle combustion model was established. The simulation validation was conducted by comparing the model prediction and the experimental results in the literature to prove the model reliability. Due to the moisture evaporation in the fuel particle, a plateau appears on the particle center temperature curve during the initial period of the thermal conversion process. Different from the cases in the pulverized coal boiler, particle temperature evolutions under different atmospheres are almost the same, indicating that the strong heat and mass transfer control the combustion process in fluidized beds.

Jia et al. obtained the mercury emission by measuring the mercury contents in flue gas and solid samples in pulverized coal (PC) and CFB boilers. The relationship was obtained between the mercury emission and fly ash adsorption characteristics. The results show that the majority of mercury released to the atmosphere with the flue gas in PC boiler, while the mercury is enriched in fly ash and captured by the precipitator in CFB boiler. The coal factor is proposed to characterize the impact of coal property on mercury emissions. The larger the coal factor, the lower the mercury emission to the atmosphere. It is also found that the mercury content of fly ash in CFB boiler is ten times higher than that in PC boiler.

Shen et al. used large eddy simulation (LES) to study the performance of a 660 MW ultra-supercritical boiler under BMCR, 75% THA-100 and 50% THA-100 conditions. The flow, heat transfer and combustion processes are systematically investigated. The predicted gas velocities agree well with the thermal calculation, and the temperature errors are less than 127 K. The simulation results show that the operation load has significant effects on the boiler performance. It is proved that LES can provide guidance for the design and operation of the advanced coal-fired boilers.

Li et al. investigates the effects of tertiary air declination angle (TDA) on the coal combustion and steam temperature characteristics in a 350 MW supercritical down-fired boiler. The experimental results indicate that as the TDA increases from 0° to 15°, the O₂ concentration decreases while the CO and NO concentrations increase in the near-burner region. The flame kernel is found to move downward, and the temperature in the hopper region increases simultaneously. The TDA change has little effect on the NO_x emissions. In comprehensive consideration of the combustion characteristics and boiler economic performance, the optimal TDA of 15° is recommended.

In general, this special column contains a select 12 of 175 papers presented at 9th ISCC, focusing on the theme of clean and highly-efficient utilization of coal. It is expected that the research contribution from these papers can provide a strong demonstration of the responsibility and active efforts of the international scientific and industrial community to ensure a green and sustainable coal utilization.

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Guest editors:

Prof. **Guangxi YUE**, Professor at the Department of Energy and Power Engineering, Tsinghua University. Prof. Yue's expertise is in areas of thermal engineering. He is well-known in the field of clean coal technology including fluidized bed combustion and coal gasification for his researches and practices. In addition to numerous research projects, from 1990s to the present, he has been leading 9 major national research projects, and several collaborated research projects across countries including Japan, France, Sweden and USA. He has been guest speaker in seminars sponsored by companies and research institutes, and keynote speaker for conferences in China, South Korea, Vietnam, Canada, USA, India, Russia, Poland, etc. In 2009, he was elected as the Academician of the Chinese Academic of Engineering. He has been leading the R&D of 600 MW supercritical CFB demonstration in China. The demonstration was already in commercial operation successfully in 2014.

Prof. **Junfu LYU**, Professor at the Department of Energy and Power Engineering, Tsinghua University. His interests lie in coal combustion, coal gasification, circulating fluidized bed combustion technology, hydrodynamic of boiler, and coal fired pollutant control. He has once organized and hold a series of the key technology research and development plant of Chinese government, the National Natural Science Foundation of China, as well as the projects from enterprises. His achievement work includes the 600 MW supercritical CFB boiler, the superheat steam generator by the salted waste water from heavy oil recovery, and the ultra-low emission circulating fluidized bed boiler technology by limestone injection into furnace and low NO_x combustion. These developed technologies have been commercialized and used widely. He was elected as the New Century Excellent Talents in University, the Outstanding Academy. He won the BEST paper award twice in 15th and 23th International Conference on Fluidized Bed Combustion. He got the first-class National Scientific & Technological Progress Award in 2017 and the second-class National Scientific & Technological Progress Award in 2005. Besides, he also won the first-class prizes in scientific & technological progress or invention from the Ministries and Commissions. He published more than 300 Journal papers and 5 books. He has more than 70 authorized invention patents.

Prof. **Shuiqing LI**, Professor at the Department of Energy and Power Engineering, Tsinghua University. He obtained both his B.S. and Ph.D. degrees from Zhejiang University and has been a visiting scientist at the University of Leeds (2004–2005), the University of Iowa (2006), Princeton University (2010–2011), Yale University (2014), and RWTH Aachen University (2018). Current research interests of Prof. Li include adhesive particulate flow, combustion physics, gas-phase material synthesis, clean coal technology. Prof. Li has more than 140 peer-reviewed papers published on *Prog. Eng. Combust. Sci.*, *Phys. Rev. Lett.*, *Soft Matter*, *J. Fluid Mech.*, etc., with about 2800 citations and H. Index of 30. He co-authored a monograph of Adhesive Particle Flow at Cambridge University Press, and holds 20 patents.

Prof. Li is a Recipient of the National Young and Middle-aged Leading Scientists, Engineers and Innovators (2018), the National Science Fund for Distinguished Young Scholars of China (2017), the National Award for New Century Excellent Talents (2009) and the Tsinghua University Award for Young Talents on Fundamental Studies (2011). Due to his outstanding achievements, he is elected a fellow of the Combustion Institute (2020).