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Clean coal geology in China: Research advance and its future

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Abstract In China, the connection between coal utilization and environmental pollution has been increasingly evident due to the rapid growth in energy consumption. Clean coal technology (CCT) is one of the effective methods to address coal-associated pollution. However, CCT needs the practical and theoretical support of clean coal geology (CCG). In this paper, a new definition of CCG is proposed, based on the definitions of coal, coal geology, and CCT, combined with the development of national CCG. CCG is the discipline comprehensively researching the genesis, nature, distribution, cleaning potential, clean utilization and environmental effects of resources (coal, coal bed methane, and other coal-associated resources) that can be cleaned by CCT. The research content of CCG is discussed from different aspects, such as cleaning potential evaluation, geological guarantee for coal mining, ash yields and sulfur contents, trace elements, pollution caused by coal, and mine reclamation. The progress of CCG in China is also briefly divided into four stages and delineated. Finally, scientific problems in CCG are summarized and an outlook for CCG is given.

Keywords Clean coal · Clean coal geology · Research content · Progress · China

1 Introduction

Coal dominates the primary energy in China and likely will remain so for the foreseeable future. This is largely because China is rich in coal but poor in petroleum and natural gas (National Bureau of Statistics of China 2018). At the same time, China is the largest consumer of coal, accounting for about 50.5% of world coal consumption in 2018 and is expected to remain so, at a proportion of about 39%, until about 2040 (BP 2019a, b). Coal, as the main energy source, promoted the economic development of China, but nevertheless also contributed to a range of environmental issues (Lin et al. 2004; Dai et al. 2006a, 2012a; Wu 2010; Brauer et al. 2013; Huang et al. 2014; Guan et al. 2014; Ma et al. 2017; Finkelman and Tian 2018).

Clean coal technology (CCT) is a key to address these environmental issues. Globally, there are many different combinations of various technologies used as CCTs in different countries and regions (Melikoglu 2018). Some of the CCTs (such as NO_x and SO_2 capture in these developed countries) are mature and others (carbon capture, utilization and storage, CCUS) are in initial stages or under development in various countries around the world (Melikoglu 2018). These less mature CCTs can be improved with economic supports from incentives and carbon-tax refunds (Melikoglu 2018). In early 2015, Academician Kechang Xie, the vice-president of the Chinese Academy of Engineering, recommended that China should speed up research and the development of CCT and its industrial utilization (Xie 2015). He

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also recommended that CCT should have independent intellectual property rights, to provide an initiative for development, as part of the development plan for coal in China in 2030 (Xie 2015). The substance of clean and efficient utilization of coal is to promote its clean use throughout the whole coal industry and the industrial chain that depends on coal (Xie 2015). The projects—clean and efficient utilization of coal and full implementation of low emissions and energy saving reforms for coal-fired units—are two of the 100 major projects in the Chinese 13th five-year plan. In 2016, experts in coal geology established the clean coal geological professional committee (Editorial office of coal geology of China 2016), which fully illustrated their attention to clean coal geology (CCG). At the 19th Communist Party of China (CPC) National Congress, promoting the reform of ecological civilization to build a livable China was proposed, the significant component of which was clean, efficient, and comprehensive utilization of coal resources. The conflict between construction of ecological civilization and pollution associated with coal utilization will promote the development of CCG in the future, which is very important for addressing such pollution.

These factors strongly indicate that CCG is of great importance and necessity. As such, this paper redefines and delineates the concept of CCG and shows its main component of research and its progress in China from geological aspects, which can provide an appropriate reference for using coal comprehensively and efficiently and for clean coal research.

2 Clean coal geology

Coal, widely used as a natural fuel, is defined as a combustible organic layered sedimentary rock with ash yield (dry basis) being less than 50%, and which usually is characterized by black or brown color (GB/T5751–2009 2009). Coal, comprised of macerals and mineral matter (Finkelman et al. 2019; Dai et al. 2020a), was formed by the biochemical and geochemical transformation of accumulated and preserved remains of plants, over the course of geological time, under the effects of temperature and pressure (Encyclopedia of China Publishing House 1993; GB/T5751–2009 2009). Usually the accumulation and transformation of the original plant material occurred in an oxygen-deficient depositional environment, such as a mire, where the plant material could be covered with water (Encyclopedia of China Publishing House 1993; GB/T5751-2009 2009; Dai et al. 2020b). Historically, coal has supported the development of Chinese industry and economy because it is cheap, readily minable, easy to transport and combust, and occurs in great reserves. But, with increasing deterioration of the environment, intensive and systematic researches on CCG and CCT are not only necessary but also imperative.

In the 1980s, the concept of clean coal was proposed by Drew Lewis and William Davis who both were dealing with the issues of acid rain pollution in the border between America and Canada (Abelson 1985, 1990). Currently, CCT has become one of the leading technologies in the world to solve environmental issues and also is a significant field of international high-tech competition (China Industrial Information Network 2016). CCT was originated from the United States, and included in the Energy Dictionary in the 1980s, which referred to advanced technologies such as the processing, conversion, combustion and pollution control, aimed at reducing emissions and improving efficiency in the whole process from mining to utilization of coal (Abelson 1985, 1990; Zheng 1996). CCT can be divided into different categories according to the processes of production or utilization, such as clean technology before coal combustion, clean combustion technology, clean technology after coal combustion, and coal conversion (Zheng 1996). In China, CCT focuses on a series of technologies, such as mining, transportation, preparation, conversion, and combustion, covering the whole process from mining to utilization of coal (Zheng 1996). In comparison, CCG emphasizes the natural and geological characteristics of coal itself and the cleaning potentials of coal resources. Tang et al. (2006) proposed that the term "clean coal" meant the coal with low pollutant emissions during preparation and utilization or the coal having good cleaning potentials. Nevertheless, we assert that "clean coal" refers more broadly to the use of processed (i.e., cleaned) coal in CCT, where clean coal can be used efficiently with low emissions.

Coal geology involves research on the components, genesis, nature, distribution, exploration, utilization, and environmental effects of coal, coal seams, coal-bearing strata, coal basins, and coal-associated mineral resources (such as coal bed methane, accompanying elements, and coal-formed oil), based on geological theories and methods. Coal geology is closely related to lithology, tectonics, sedimentology, geology of ore deposits, geophysics, and petroleum geology (Yang and Han 1979; Yang and Zhou 1996; Huang and Zhang 2005; Cao et al. 2010). A definition of CCG given by Tang et al. (2006) was that it is the research discipline concerning the availability of coal and the abundance, distribution, modes of occurrence, transformations, and effects on human health of trace elements in coal, on the basis of in-depth understanding of environmental factors. Thus, CCG is a new field formed by combination and integration of coal geology, environmental science, CCT, chemistry, and biology. To the best of our knowledge, no one outside of China has proposed such a definition of CCG.

A new definition of CCG is proposed in the present paper. Specifically, CCG is the discipline comprehensively researching the genesis, nature, distribution, cleaning potential, clean utilization and environmental effects of resources (coal, coal bed methane, and other coal-associated resources) that can be cleaned by CCT.CCG uses a multi-disciplinary approach, combining the theories and methods of geology, petrology, chemistry, mineralogy, environmental science, mathematical statistics, and coal technology. CCG also can incorporate aspects of coal cleaning assessments, geophysics, hydrogeology, mining geology, mine reclamation, coal preparation, coal conversion, and clean utilization of coal. The primary aim of CCG is to maximize the utilization of the valuable components in coal and to minimize the discharge of the undesirable or potentially harmful parts. CCG, combined with CCT, predicts and evaluates the emissions from coal during processing, conversion, and utilization.

3 Research directions of clean coal geology

The research directions of CCG include, but are not limited to, cleaning potential evaluation of coal resources, geological guarantee for safe and efficient mining (providing geological information, such as faults, folding, and thickness of coal seams for mining), measuring ash yields, sulfur contents, trace elements in coal, preventing and controlling of emissions associated with coal utilization, and mine reclamation, as shown in Fig. 1.

3.1 Evaluation of cleaning potentials

The cleaning potential evaluation of coal resources is done to assess quality and cleaning potentials of coal according to related data (such as ash yields, sulfur contents, and contents of potentially hazardous trace elements) and to classify and delineate coal resources of different qualities and cleaning potentials, to provide the geological basis for exploitation of different coal resources. Coal quality is expressed as the classification of raw coal based on ash yields, sulfur contents, and hazardous trace elements (Tang et al. 2012, 2013). Cleaning grade usually corresponds to the quality of the coals treated by CCT (Yang et al. 2011). Cleaning potential refers to the degree of removal of minerals, and potentially hazardous trace elements in coal after coal preparation (Tang et al. 2017).

Coal quality is classified based on the indexes of ash yield, sulfur content, and calorific value, which were graded by the National Coal Standardization Technical Committee of China in 1994, 2004, 2010, and 2018 (GB/T 15224–1994 1994; GB/T 15224–2004 2004; GB/T 15224–2010 2010; GB/T 15224–2018 2018). The ash yields and sulfur contents of Chinese coals were graded and summarized during the third national coalfield assessment with the quality of coal being classified, based on parameters such as ash yield, sulfur content, calorific value and washability (Mao and Xu, 1999; Yuan, 1999). The concept of high-quality coal was proposed by Yuan (1999) and redefined by Li et al. (2008) in the study of Chinese western coal resources, and was used to evaluate and delineate favorable areas of high-quality coal resources in the Ordos Basin. According to geological characteristics of coal, the quality of coal was divided into six grades by Tang et al. (2012, 2013). Their approach was applied to coal resource evaluation in Shanxi Provence and in Inner Mongolia. Grade definition and regional division of cleaning potentials of coal resources are one of the main research components of CCG (Tang and Ma 2005; Tang

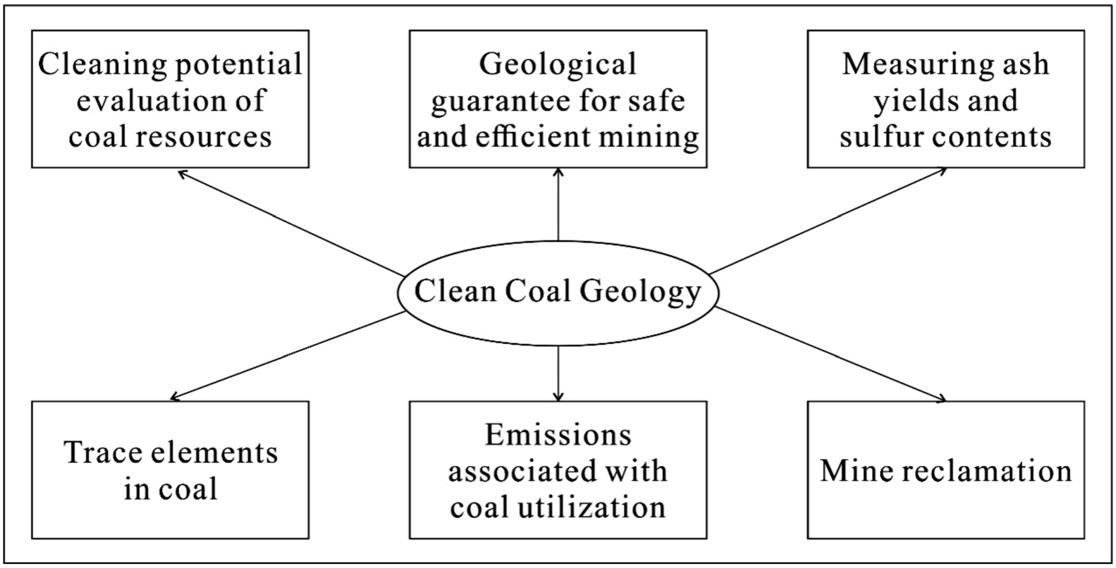

Fig. 1 Main directions of CCG research

et al. 2006). At present, there are several cleaning potential evaluation systems in China: the four-grade scheme (Wang et al. 2005; Wang and Qin 2011), the five-grade classification schemes adopted by the geological study of clean coal in China organized by the China National Administration of Coal Geology (Tang et al. 2006), and the six-grade scheme, proposed by Yang et al. (2011) and used for coal resource evaluation in such provinces as Guizhou, Anhui, and Shanxi. In areas where geological information was relatively complete, coals were classified as clean, subclean, less clean and unclean resources by Tang et al. (2006). This method was used to the evaluate coal resources in the West Guizhou-East Yunnan area. By comparing the characteristics before and after coal preparation, a formula for calculating coal cleanability was proposed by Tang et al. (2017) and used to evaluate coal resources in Shanxi province (Wang et al. 2018; Tang et al. 2020) The cleaning potentials of coal resources were classified into five categories according to cleanability (Tang et al. 2017).

The classification schemes of cleaning potential proposed by different scholars (Wang et al. 2005; Tang SH et al. 2006 Wang and Qin 2011; Yang et al. 2011; Tang YG et al. 2012, 2013, 2017) are different, although the indexes adopted in evaluation systems are similar. In brief, these evaluation indexes can be summarized in three categories: ash yields, sulfur contents and hazardous trace elements. For the evaluation of coal resources in large regions (such as the entire nation, or in one particular province), the indexes of ash yields and sulfur contents are usually used because of the deficiency of hazardous trace element data.

3.2 Ash yields and sulfur

Ash is the residue of coal combustion or conversion. Ash yields are related to the amount of mineral matter in coal (Gluskoter 1975; Ward 2002, 2016) and to the conditions used to create and measure the ash (Yang and Han 1979; Suárez-Ruiz and Crelling 2008; GB/T 212–2008 2008). There are several earlier researches about distribution of coals with different ash yields in China (Li and Zhai 1992; Li and Fei 1996; Yuan 1999). These studies showed that Chinese commercial coals have primarily low-medium (10.01%–20.00%) and medium (20.01%–30.00%) ash yields. The latest national potential evaluation of coal resources in China showed that the lowest reserve-weighted average ash yield is associated with the early and middle Jurassic coals and the highest is associated with the Paleogene coals (Tang et al. 2013). Coals, formed from terrestrial sources, usually have high ash yields (> 30%) while coals that formed in a paralic environment often have low ash yields (< 20%) and high sulfur contents (> 2%) (Tang et al. 2013). Most coals in China have low-medium and medium ash yields. The ash yields of coal resources in southern China are generally higher than those of coal resources in northern China (Yang 2015). We suggest that studies on ash should gradually evolve into having a major focus on the nature, composition, environment effects, and recycling and utilization of coal ash.

Sulfur is one of the harmful elements in coal. It displays two forms of occurrence—inorganic and organic sulfur (Chou 2012; Tang et al. 2015). The traditional “forms of sulfur” analysis reports pyritic sulfur (pyrite and marcasite), sulfatic sulfur (gypsum, iron sulfates, etc.), and organic sulfur. Organic and pyritic sulfur in coal are combustible, and will release harmful SO_2 during coal combustion. In the early 20th century, American scholars Thissen and White began studying sulfur in coal (White 1913). There are many researches on sulfur in Chinese coal (Hong et al. 1992; Chen 1994; Li and Zhai 1994; Tang 1993; Ren et al. 1994; Lei et al. 1995; Li 1998; Chou 1999; Zhou et al. 1999, 2000; Tang et al. 2002; Hu et al. 2005a, b; Luo et al. 2005; Dai et al. 2008; Tang et al. 2015). These studies on sulfur in coal tend to focus either on organic sulfur or on inorganic sulfur. Domestic researches on inorganic sulfur began earlier than organic sulfur. The studies on inorganic sulfur mainly include the nature and genesis of pyritic sulfur (Tang 1993; Tang and Ren 1996; Liu et al. 2000), and the removal of inorganic sulfur (Thoms 1995; Liu 2015). Researches on organic sulfur examine the structure of organosulfur compounds in coal, occurrence, geological genesis, distribution, and removal (Kang et al. 1999; Tang et al. 2002; Hu et al. 2005a; Du 2014; Wei et al. 2015). It is easier to remove inorganic sulfur than to remove organic sulfur in coal (Chen 1994; Chou 1997; Dai et al. 2000a; Chou 2012). Recently, there have been studies on the removal of organic and inorganic sulfur using microwave treatments (Cai 2013; Wei et al. 2018; Xu and Tao 2018). The statistical results of the reserve-weighted average of the sulfur contents in coal showed that the range of sulfur contents in Chinese coals is wide (0.02%–10.48%) (Tang et al. 2015). Sulfur contents in the late Permian coals are the highest, followed by the late Carboniferous coals, and those of the early and middle Jurassic coals are the lowest (Luo et al. 2005; Tang et al. 2015).

3.3 Trace elements in coal

Trace elements in coal, with content less than 1 wt%., include most elements in the periodic table (Tang and Huang 2004). More than 80 trace elements can be detected in coal, coal combustion products, and coal-bed methane (Tang and Huang 2004). Finkelman (1995) discussed the environmentally sensitive trace elements in coal. Hazardous trace elements, including 22 kinds by listed Ren et al. (1999a), refer to those trace elements that are toxic, radioactive, carcinogenic or potentially harmful to the environment (Zhao 1997; Zhao et al. 1998; Ren et al. 1999a, 2006). Swaine (2000) studied the environmental interest in trace elements in coal.

There are many researches on trace elements in domestic Chinese coals (Chen et al. 1986; Sun and Jervis 1986; Wang and Ren 1994; Huang et al. 1999, 2001; Liu et al. 1999a; b; Ren et al. 1999a, b; Bai et al. 2004; Tang and Huang 2004; Dai et al. 2006b, 2012a, b, 2014, 2018; Song et al. 2010; Cheng et al. 2013; Bai et al. 2014, 2017a, b; Xie et al. 2014; Zhang et al. 2016; Zhou et al. 2017; Wang et al. 2019b) and in coals from other nations (Gluskoter 1975; Bouška 1981; Swaine 1990, 2000; Swaine and Goodarzi 1995; Finkelman 1993, 1995; Finkelman and Gross 1999; Ketris and Yudovich 2009; Say-Gee and Wan 2011; Nakajima and Taira 2014; Hot et al. 2016; Arbuzov et al. 2019). The authoritative background values of trace elements in Chinese coals were obtained by Dai et al. (2012a, b) and an evaluation formula of enrichment coefficients of trace elements was established by Dai et al. (2014). Recently, the emphases of researches on trace elements are on their behavior during coal utilization (Tang et al. 2018a; b), their health impacts (Dai et al. 2014; Finkelman and Tian 2018), and recovery of valuable trace elements (Dai et al. 2006b; Seredin and Dai 2012; Dai et al. 2014, 2016; Dai and Finkelman 2017). This last topic is illustrated by the fact that germanium has achieved industrial extraction (Tang and Huang 2004).

The national Key Basic Research Programon Distribution and Enrichment Mechanisms of Hazardous Elements in Coal and Preventing and Controlling of Environmental Pollution, for which Prof. Shifeng Dai was mainly responsible, focused on five hazardous elements (mercury, arsenic, fluorine, beryllium, and uranium), and directed national attention to research on trace elements in coal. Many of the trace elements in coal are capable of occurring in more than one chemical form. Consequently, they can also have different physical, chemical, and biological properties and can exhibit different environmental migration capacities when in their different forms. Understanding the chemical form, fate and behavior, and enrichment tendency of hazardous elements during coal utilization is of great significance to accurately evaluate their potential hazards to human health and to the environment, and to control their emissions.

3.4 Geological guarantee for safe and efficient mining

Geological guarantee technology for safe and efficient coal mining is one of the key technologies for mining proposed at the beginning of the 21st century. It mainly includes the technology for prediction of changes in thickness of a coal seam, prediction of surrounding rock stabilities, prediction of geological structural conditions, prediction of hydrogeological conditions, high-resolution detection of underground structures from the surface, and the drilling technology (Wu et al. 2000; Peng et al. 2001, 2007; Liu et al. 2004). The mine geological guarantee system for high-yield and high-efficiency, based on the characteristics of mechanization and higher centralization of the mine, taking geological quantification as the guide, seeks to realize dynamic management of geological work by means of comprehensive technologies such as geophysical prospecting, drilling, and advanced computer technology (Peng et al. 2007). It also seeks to provide reliable geological guarantee for all aspects and stages involved in mine designing, mining area arranging, production preparation, mining face arranging, and back-stoping (Peng et al. 2007).

In the process of coal mining, a reasonable mining plan should be formulated with consideration of the geological structural factors and according to basic geological data to realize efficient and safe mining (Meng et al. 2012). The green coal mining technology, originally proposed by Minggao Qian, Academician of Chinese Academy of Engineering, in 2003, referred to technology that aimed at reducing environmental damage and waste of resources during mining, improving the economic benefits of coal enterprises, coordinating mining with environmental concerns, and eventually achieving high efficiency and low emissions (Qian 2003). Since 2000, researches on co-mining of coal and coalbed methane have gradually increased (Li and Xu 2002; Yuan 2009; Liu 2015; Ji 2015; Zhang et al. 2017). Co-mining technologies of coal and gas include pre-mining extraction of gas, gas extraction during mining, and gas extraction after mining (Tao 2012). Recently, most of these researches focus on coalbed - methane in outburst coal seams (Tao 2012; Ji 2015; Liu 2015). For Chinese CCG, co-mining of coal and gas is significant for improving coal mine safety conditions, improving coal mine production efficiency and economic efficiency, and reducing carbon dioxide emissions. With continuous high-intensity mining of coal resources, the shallow resources were progressively exhausted and the depth of mining was gradually increasing. Therefore, research on geological guarantees for mining of deep coal resources was also carried out (Jia et al. 2012; Hu 2013). Academician of Chinese Academy of Engineering Suping Peng summarized and provided a prospect of the research on the development of mining and geological evaluation of deep coal resources, and put forward four key scientific problems urgently needed to be solved for the development of deep coal resources (Peng 2008). They are (1) the environment of formation of deep coal resources and its effect on coal seams and coal quality, (2) the distribution of high crustal stress, high geothermal gradients, and high volumes confined water in the deep part of a coal mine, (3) theories for the detection and methods of occurrence of such conditions in deep coal resources, and (4) theories and methods for exploration and evaluation of deep coal resources (Peng 2008). This work clearly indicated the necessity and importance of fundamental geological research for safe and efficient coal mining.

Much research has been done on geological guarantee for mining of coal resources in different areas or in different geological conditions (Qin et al. 2014; Cao et al. 2018; Xie et al. 2018; Wang et al. 2019a). With the development of coal exploration technology, a new system of theory and technology for comprehensive coal geological exploration with its own Chinese characteristics was established (Wang 2013) and a new concept of "green coal resources" was proposed (Wang et al. 2017b; Yuan et al. 2018). This new concept can provide geological and technological support for guaranteeing national energy security (Zhao 2018). The new coal geological exploration technology mainly includes six aspects. They are the geological guarantee technology for exploration and green mining of green coal resources, the geological guarantee technology for co-exploration and mining of coal-associated mineral resources, the geological guarantee technology for "geology+" serving the construction of ecological civilization, the comprehensive management and utilization technology for the closure of mines and remediation of mining subsidence areas, the geological guarantee technology for the energy and mineral resources in the "Belt and Road Initiative" areas, and promoting the "Internet+" action (Zhao 2018).

3.5 Coal-associated pollution and mine reclamation

The coal-associated impacts on environment and human health can be divided into four categories according to different processes (Finkelman 1995, 1999; Finkelman and Gross 1999; Finkelman et al. 1999; Suárez-Ruiz and Crelling 2008; Finkelman and Tian 2018): the environmental impacts of underground coal seams, mainly including leaching of hazardous substances and in-situ combustion to release greenhouse gases; the environmental impacts from coal mining, mainly involving visual blight, land subsidence, quality degradation of surface and underground water, the desolation of farmland, and ecological deterioration; the environmental impacts of coal transportation and processing, mainly consisting of dust, spontaneous combustion, leaching, gangue, and coal washing sewage; and the environmental impacts from coal combustion, mainly including thermal pollution, acid rain, smog, climate change, the release of hazardous trace elements, and coal combustion products (CCPs) (Finkelman et al. 1999; Lin et al. 2004; Suárez-Ruiz and Crelling 2008; Dai et al. 2006a, 2012a; Wu 2010; Huang et al. 2014; Guan et al. 2014; Ma et al. 2017). Comprehensive use of "coal green mining technology" can greatly reduce environmental pollution associated with coal mining, including water conservation technologies, filling and strip-mining technology with separation grouting, coal and gas co-mining technology, coal seam roadway supporting technology, the technology of reducing gangue emissions, and underground gasification technology (Qian 2003). CCT is effective at preventing and controlling pollution caused by coal processing and utilization (Zheng 1996). Methods to prevent and control pollution associated with coal combustion can be divided into three types: cleaning and processing the coal before combustion, improving process conditions during combustion to make coal fully burned, and treatment of flue gas after combustion to reduce emissions (Zheng 1996). Vigorously developing and promoting CCT is key to effectively prevent and control coal-source pollution. As we discuss in this paper, CCT needs the support of CCG.

Mine reclamation involves the series of activities or processes that take measures to remediate the ecological damage and environmental pollution caused by mining, and to recover or restore the land to the situation it was in before mining began. Reclamation is aimed at the protection of the regional ecological environment in the same time frame as mining (Hu et al. 2005a, b). Since the later 20th century, mine reclamation has gradually become a research focus of many scholars (Hu et al. 2005a, b, 2008, 2011, 2014, 2016; Wang et al. 2010; Bian 2011; Bi et al. 2014; Bi 2017; Wang et al. 2017a). Recently, the "One Belt and One Road Initiative" also brought opportunities and challenges to research on mine reclamation (Hu 2016). Mine reclamation is consistent with the spirit of constructing an ecological civilization in China, an undertaking which needs continuous inputs from research.

4 Progress of clean coal geology in China

The progress of CCG in China can be divided into four stages, each of which covers a period of about 10 years. Focused efforts on CCG began in the 1980s.

The beginning stage (1980–1990): In China, the earliest geological systematic research related to coal preparation began in the 1980s with the studies on sulfur occurrence and washability of coals from Nantong and Songzao coal fields in Chongqing, China carried out by Ren et al. (1994) and by other scholars (Su and Ren 1992; Tang et al. 1993, 1995).

The exploring stage (1990–2000): In the 1990s, the occurrence and removal of sulfur and minerals in coals from the Wuda coal field in Inner Mongolia was studied by Hou et al. (1997),Tang et al. (1999), and Dai et al. (2000b). These researches were mainly about coal preparation and processing.

The mature stage (2000–2010): Geological technology and dynamic evaluation were used to study the clean utilization of coals in Wuda coalfield (Li 2000). In 2002, the geological technology of clean use of coal, carried out by Prof. Yuegang Tang, was honored the provincial First Prize of Scientific and Technological Progress by the Ministry of Education of the People's Republic of China. Systematic research on CCG of resources in China was published by Tang et al. (2006), with a focus on the nature and transformation of sulfur and potentially hazardous trace elements in coal. In this research, systems of cleaning potential evaluation were established and applied to nation wide coal resources (Tang et al. 2006). The organic geochemistry of trace elements in coal was also studied (Zhu et al. 2001, 2003, 2005; Liu et al. 2003; Zheng et al. 2006), supported by the Natural Science Foundation Project "Average Chemical Composition of Chinese Coals and Organic Geochemistry of Hazardous Elements in Coal" with leadership by Prof. Baoshan Zheng. Geological and geochemical theories and evaluation of cleaning potentials began to be applied to guide the clean utilization of coal, corresponding to the mature stage of CCG in China.

The establishment stage (2010-the present): The latest potential evaluation of national coal resources (Tang et al. 2013) has been finished. Two evaluation systems—for coal quality (Tang et al. 2012) and for cleaning potential (Yang et al. 2011)—were used in this evaluation work. Additionally, the clean coal geological professional committee was established in Changsha, Hunan province in 2016. These studies and the information they produced marked the establishment stage of Chinese CCG. In recent years, there have been some new achievements in CCG in China, such as the concept of cleanability proposed by Tang et al. (2017), studies of the behaviors of potentially hazardous trace elements during coal gasification (Tang et al. 2018a, b; Wang et al. 2019b), a review of valuable elements in Chinese coals (Dai et al. 2016), and studies of the health impacts of coal utilization (Finkelman and Tian 2018). Nevertheless, these researches are only some of the component parts of the overall field of CCG. There remains much additional work needing to be done in CGG, such as investigations of the complex transformations of mineral matter during different coal utilization processes, the relationship between the behavior of mineral matter and its geological origin, and the optimum means of utilizing coals with different qualities.

5 Summary

CCG was redefined as the discipline comprehensively researching the genesis, nature, distribution, cleaning potential, clean utilization and environmental effects of coal resources that can be cleaned by CCT.

The research contents of CCG involve investigating and establishing the cleaning potential evaluation of coals, geological guarantee for safe and efficient coal mining, sulfur and mineral matter contents in coal, preventing and controlling of emissions associated with coal, and coal mine reclamation.

The progress of CCG in China can be divided into four stages—the beginning, exploring, mature, and establishment stages. In China, there have been some new achievements in CCG in recent years, but there remain many scientific problems that needed further research.

6 Challenge and forecast

CCG in China has been rapidly developed for about 40 years as a new, diverse, and comprehensive discipline. Nevertheless, there still are several scientific problems in the research field of CCG, shown as follows.

(1) The health impacts of a single element need to be evaluated in light of the fact that there could be synergy or antagonism between the effects of the element being studied and the many other elements that may also affect health.

(2) Comprehensive analysis of mass balances around coal utilization process is weak and there is no systemic cleanability index that indicates the cleaning potential of coals through the whole process from mining to utilization.

(3) Because of the complexity, diversity, and multiplicity of the geological settings of coal in China, the mode of occurrence of hazardous substances in coal has a great temporal and spatial variation. All the same, there has not yet been research on the distribution of coals with different cleaning characteristics from the endogenetic and exogenetic geological processes of a coal basin.

(4) The relationship between the geologic genesis of potentially hazardous substances in coal and the technology of coal utilization is poorly explored, which in turn means that the distribution, transformation, and removal mechanism of hazardous materials having different geologic genesis needs to be researched during different coal utilization processes.

(5) The prevention and controlling of emissions and pollution associated with hazardous trace elements in coal are not yet strongly established.

(6) A comprehensive evaluation system of cleaning potential, consisting of selection of indices, calculation of weighted values, evaluation methods, and classification schemes for cleaning potentials, remains to be established.

The policies adjusting the structure of primary energy use and controlling carbon emissions are favorable for coal only if it is utilized very efficiently. At the same time, these policies promote further research in CCG, such developing routes to coal-derived graphene, and studying the prospects for coal use as fertilizer. The results of these and many other studies can provide a reference for improving the utilization efficiency and the reduction of emissions. As for CCT, effective CCUS and the prediction and control of the rapid and complex changes of mineral matter during coal combustion, gasification, liquefaction, and pyrolysis are major scientific challenges. The basic materials and data regarding the cleaning potentials of national coal resources remain to be established. Additionally, the combination of CCG with CCT is of great significance for the development of CCG.

Biology, physics, and artificial intelligence (AI) are significant fields of scientific development in the future, all of which provide opportunities and challenges for the development of CCG in China. The development of modern biology will bring new insights and methods into the studies on coal formation, on the utilization of organic components in coal, and on biological processing of coal using enzymes or microorganisms. Physics will provide new methods for research on microstructure of coal to reveal precisely the modes of occurrence of hazardous elements in coal. Such improved information likely will provide basic data for the evaluation of cleaning potentials. Using data on ash yields, sulfur contents, and hazardous trace elements, the space–time distribution of coal with different cleaning potentials can be achieved by applying AI technology and techniques for meta-analysis of large data sets, the results of which can provide a reference for efficient mining and clean utilization of coal resources.

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