Clean Coal Technologies in China: Current Status and Future Perspectives

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\section{1. Introduction}

Coal is the dominant primary energy source in China, accounting for about 64\% of the total primary energy consumption in 2015 [1]. It is the major source and material for power generation, energy-intensive industries (steel, cement, etc.), and residential and commercial heating. In addition, it is a major source of greenhouse gases (GHGs) and air pollutants in China. In 2013, about $9.0231 \times 10^9$ t of carbon dioxide (CO\textsubscript{2}) were emitted from fuel combustion in China, with more than 83\% coming from the combustion of coal [2]. In 2012, about 79\% of sulfur dioxide (SO\textsubscript{2}), 57\% of nitrogen oxides (NO\textsubscript{x}), and 44\% of particulate matter (PM) came from the direct combustion of coal, and about 93\% of SO\textsubscript{2}, 70\% of NO\textsubscript{x}, and 67\% of PM emissions came from all kinds of coal utilization (including direct combustion emission and emission from coke stoves and other industrial furnaces) [3]. Although a great number of policy measures have been launched to control the consumption of coal in order to address climate change and alleviate air pollution, it is projected that coal will still play a dominant role in China’s energy consumption portfolio—over 50\% by 2030 [4] and around 30\% by 2050—even considering the high penetration of renewable energy [5]. Therefore, it is necessary to develop more efficient and clean technology options to enable China to continue to benefit from using its abundant and affordable coal resources.

Clean coal technologies (CCTs) are technologies that facilitate the use of coal in an environmentally satisfactory and economically viable way [6]. China has made remarkable progress in recent years in CCTs development. By the end of 2014, the installation capacity of ultra-supercritical coal-fired plants exceeded 100 GW. A 250 MW integrated gasification combined cycle (IGCC) demonstration power plant was put into operation. Localized water slurry gasification and dry feed pressurized gasification technology with a capacity of more than $2000$ t·d\textsuperscript{-1} has been realized. The world’s first coal direct liquefaction plant, with a capacity of more than $1$ Mt·a\textsuperscript{-1} (oil), was completed in 2008. The commercial demonstration plants of coal-to-olefin have also been built. Indirect coal liquefaction plants with capacities of 160–180 kt have been built. Ultra-low-emission coal-fired power generation technology has been successfully demonstrated. Successful operation of 100 kt CO\textsubscript{2} capture industrial equipment in a power plant has occurred. An enhanced oil recovery (EOR) demonstration project with a capacity of 150 kt and a CO\textsubscript{2} geological storage demonstration project with a capacity of 100 kt have been completed.

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Innovation and adoption of these technologies has played and will continue to play an important role in the green low-carbon transformation of China.

CCTs cover a wide range of coal production and utilization-related technologies, including green mining, coal purification, high-efficiency power generation, advanced coal conversion, pollution control, and carbon capture, utilization, and storage (CCUS). In the paper, current status and future perspectives of four kinds of CCTs in China are introduced sequentially as coal power generation, coal conversion, pollution control in coal-fired power plants, and CCUS.

2. Coal power generation

Coal-fired power generation technologies mainly consist of the traditional direct combustion of coal and the new coal gasification power generation technical routes. Regarding the direct combustion of coal, subcritical, supercritical, ultra-supercritical, and circulating fluidized bed (CFB) power generation technologies are widely used today. Coal gasification power generation technology mainly involves IGCC technology, an advanced power generation technology with high power generation efficiency and excellent environmental performance.

2.1. Current status

In the 11th Five-Year Plan (2006–2010) for national economic and social development, the government stipulated a targeted 20% reduction in energy consumption per unit gross domestic product (GDP) in 2010 relative to that in 2005, and a 10% reduction in SO2 emissions. To meet this target while continuing the robust development of China’s power industry, China promoted a program of “shutting down small-scale thermal power plants” in order to replace small units with large ones in 2007. Meanwhile, China also conducted research into developing supercritical and ultra-supercritical units with power generation capacities over 600 MW [7]. High-efficiency and clean power generation technologies were applied to transform existing old thermal power units. These measures greatly improved the efficiency of thermal power generation industry in China. During the period of the 12th Five-Year Plan, China conducted basic research into 700 °C ultra-supercritical power generation [8]. Researches into CFB and IGCC were also further conducted [9,10]. And the commercial demonstration of the largest 600 MW supercritical CFB boiler units in the world was put into operation [9].

This achievement greatly contributed to the optimization of the thermal power industry structure, the comprehensive enhancement of coal-fired power generation efficiency, and the reduction of pollutant emissions. The power supply coal consumption rate reduced significantly these years as shown in Fig. 1 [11,12].

2.1.1. Supercritical and ultra-supercritical coal-fired power generation technology

China has now realized the great leap forward development of ultra-supercritical coal-fired power generation technology. By the end of 2014, the total installed capacity of ultra-supercritical units exceeded 100 GW, and these units formed the majority of newly constructed units in China. One of the 1000 MW ultra-supercritical thermal power projects in China, the Shanghai Waigaoqiao No. 3 power plant, implemented a series of innovations and optimizations toward energy saving and emission reduction. A coal consumption rate of 276 gce·(kW·h)−1 (gce means gram coal equivalent) was attained by the plant, reaching the forefront of the international level.

Chinese researchers developed a 600 MW large-scale air-cooling system, and developed and constructed the world’s first 1000 MW ultra-supercritical air-cooling unit. The total installed capacity of the units equipped with the air-cooling system now reaches 66 GW.

The 1000 MW double-reheat ultra-supercritical units have been built in China with efficiency more than 47% [13]. Two sets of 1000 MW double-reheat ultra-supercritical units at the Guodian-Taizhou power plant completed their grid connection in 2015. The power supply coal consumption rate of these sets has achieved 266.53 gce·(kW·h)−1. Each unit of the plant is designed and manufactured entirely in China, and currently exhibits the world’s highest parameters and highest efficiency. The technology of these double-reheat ultra-supercritical units has been applied in three power plants.

China now has the foundation and ability to design and manufacture 600 MW/1000 MW ultra-supercritical generator units. Chinese researchers have also gathered rich experience in the operation of 600 MW/1000 MW ultra-supercritical generator unit boilers. Units designed and manufactured in China have been exported to foreign countries. These achievements have established a solid technological foundation for the further development of supercritical power generation technology with higher parameters (exceeding 600 °C and 700 °C).

2.1.2. Supercritical CFB boiler power generation technology

A large proportion of China’s coal resources has a high sulfur content. The coal-washing process produces a large amount of coal gangue that needs to be used. CFB combustion technology, with its wide fuel scope, low cost of desulfurization, and low NOx emissions, has the advantage of largely using this kind of fuel. Thus far, China’s CFB combustion boiler power generation capacity is nearly 100 GW and includes a total of more than 3000 CFB boiler units—the largest number of such units in the world.

Regarding the large-scale capacity of CFB boiler technology in China, research, manufacturing, and demonstration operations at the 300 MW level have been completed, and batch production has been achieved. The 600 MW supercritical CFB boiler demonstration project that was developed, designed, and manufactured domestically has been put into commercial operation in Baima, Sichuan (Fig. 2) [14]. It is designed for coal with high ash content and high sulfur content and for lean coal with low calorific value. The project comprises a CFB boiler design system and product system [14,15].

2.1.3. IGCC technology

Six coal-based IGCC power stations have been put into operation around the world to date, including two in the US, two in Europe, one in Japan, and one in China. The 330 MW IGCC demonstration project owned by the European Union (EU) has the largest unit capacity in the world of any IGCC power station, with its net efficiency of 45% (lower heating value, or LHV). Researches into the H-class
lacks large-scale energy storage sections, coal power has become the primary means of balancing the power grid. Coal subsystems that are used to provide a rapid response to frequent changes in load experience decreased system performance and component life. Thus, a major problem is how to strengthen the overall system load rapid response capability, and how to retain an efficient response with clean operation. The system control strategy can be optimized for high flexibility of coal-fired power plants in the large-scale renewable energy power grid. Achieving flexible operation is the main direction for the future development of coal utilization technologies. The researches on new design methods for system flexibility and control strategies for running operation are carried on in China.

3. Coal conversion

3.1. Current status

Gasification is a very efficient method for converting solid fuels into gas fuels, starting from many different types of organic material [20]. It is one of the most important upstream technologies of the entire conversion process, which further produces liquid fuels, SNG, chemicals, hydrogen, and so forth. Pressurized gasification technologies—that is, General Electric’s pressurized
gasification technology with water coal slurry and Shell's dry feed pressurized gasification technology—have already been widely used in the chemical industry in China [21]. In the last decade, many new gasification technologies have been developed and rapidly progressed.

Entrained-flow gasification technology has reached the commercial stage (Table 1):

1. Multi-opposed-burner coal water slurry gasification has been developed by the East China University of Science and Technology (ECUST). During the period of the 10th Five-Year Plan (2001–2005), two demonstration plants were built with the capacities of 750 t·d⁻¹ and 1150 t·d⁻¹ [23]. During the period of the 11th Five-Year Plan (2006–2010), several larger-scale units with a capacity of 2000 t·d⁻¹ were constructed. In 2014, a larger unit with a capacity of 3000 t·d⁻¹ was put into operation in the Inner Mongolia Autonomous Region.

2. (Non)-molten slag-grading gasification technology, also called the Tsinghua gasifier, has been continually upgraded from the first generation in 2002 to the third generation plus in 2015. Two gasifiers with a capacity of 500 t·d⁻¹ were successfully run in 2006; since then, more than 30 gasifiers using Tsinghua technology have been put into operation.

3. In 2004, the Xi'an Thermal Power Research Institute Co., Ltd. conducted a pilot-scale test of a 36–40 t·d⁻¹ (10 MW) two-stage dry pulverized coal pressurized gasifier [24]. The same technology was also applied in the Tianjin IGCC project of the China Huaneng Group in 2012; this gasifier had a capacity of 2000 t·d⁻¹.

4. Other entrained-flow pressurized gasification technologies, such as multi-component slurry gasification technology, the dry powder gasification process with a single burner, and crushed coal pressurized gasification, have also been developed and built in commercial demonstration plants with capacities of 1000–3000 t·d⁻¹.

Research into new gasification technologies has also been conducted. An underground coal gasification demonstration base was built by the ENN Group and started to produce gas in 2009, with a daily gas production of up to 3 × 10⁵ m³ and an accumulative generated electricity of over 4.7 GW·h. This technology has realized continuous and stable gasification to date [25]. However, the problems of underground pollution and sustainable operation are still two major challenges to be addressed in the future. Other advanced gasification technologies, such as catalytic gasification, hydro-gasification, and supercritical gasification, have also been widely explored, and several small-scale pilot plants have been built.

### 3.1.2. Coal liquefaction

In the field of coal liquefaction, the Shenhua Group built the world's first and largest 1 Mt·a⁻¹ direct liquefaction facility in 2004. This facility has been successfully put into operation at the end of 2008. The final products of the facility include diesel fuel, naphtha, and liquefied gas. Spaceflight kerosene and aviation jet fuel from the coal liquefaction process have also been tested recently at this facility. A rocket engine powered by liquid oxygen coal-based spaceflight kerosene was jointly developed by the Shenhua Group and the China Aerospace Science and Technology Corporation. Trial operation of this engine was completed in 2015 [26]. A coal and oil co-processing technology demonstration plant with a capacity of 450 kt·a⁻¹ has also been built by the Shaanxi Yanchang Petroleum (Group) Co., Ltd.

In the field of indirect liquefaction, Institute of Coal Chemistry and Lu'an Group are conducting researches into low-temperature slurry bed technology, high-temperature slurry bed technology, and high-temperature fixed fluidized bed technology [27,28]. During the period of the 10th Five-Year Plan, three indirect liquefaction pilot plants were built with capacities of 160 kt·a⁻¹, 160 kt·a⁻¹, and 180 kt·a⁻¹, respectively [28]. A demonstration project of a low-temperature slurry bed with 1 Mt·a⁻¹ capacity is

### Table 1

| Coal conversion technologies          | Status by 2015 | Descriptions                                                                                      |
|--------------------------------------|----------------|--------------------------------------------------------------------------------------------------|
| Coal gasification                    |                | More than 100 gasifiers have been built or are planned to be built                                |
| Fluidized gasification               | Commercial     | Pilot test has been completed; commercial demonstration is now in progress                      |
|                                     | Demonstration  | Applied widely in China with most of the technologies being introduced from abroad               |
| Fixed-bed gasification               | Mature         |                                                                                                 |
| Underground coal gasification        | Demonstration  | A demonstration project has been operated successfully                                           |
| Catalytic gasification               | Pilot          | Pilot tests are in progress                                                                      |
| Hydro-gasification                   | Pilot          | Pilot tests are in progress                                                                      |
| Supercritical gasification           | Pilot          | The largest pilot plant test platform (6 t·d⁻¹) in China was established in 2011                  |
| Coal liquefaction                    |                | The world's first and largest commercial plant has been operated successfully                    |
| Direct                               | Commercial     | Several large-scale demonstration plants have been built                                         |
| Indirect                             | Commercial     | Domestic researches are still at the stage of pilot research, with some going through the        |
|                                      | Pilot          | industrial sidetrack test successfully                                                           |
| Coal-to-SNG                          |                | Commercial demonstration plants have been built based on various pathways, such as dimethylether/|
|                                      | Demonstration  | (coal-to-MTO)                                                                                  |
| Coal-to-olefin                       | Demonstration  | A demonstration test has been completed; demonstration plants are under construction             |
| Coal-to-methanol-to-olefin (coal-to-MTO)| Demonstration/| A new catalyst has reportedly been developed                                                    |
| Coal-to-methanol-to-propylene (coal-to-MTP)| Pilot     |                                                                                                 |
| Syngas selective conversion to light olefin | Laboratory |                                                                                                 |
| Coal-to-methanol-to-aromatics        | Demonstration  | A pilot test has been completed; demonstration plants are under construction                    |
| Coal-to-methanol-to-ethylene glycol  | Demonstration  | Demonstration plants have been constructed                                                       |
| Low-rank coal pyrolysis              | Pilot & demonstration | Pilot and demonstration projects have been built based on various pyrolyzers, such as        |

The status-rating method is in line with that of the Electric Power Research Institute (EPRI) [22]. "Mature" indicates significant commercial experience (several operating commercial units); "commercial" indicates nascent commercial experience; "demonstration" indicates a concept verified by an integrated demonstration unit; "pilot" indicates a concept verified by small pilot facility; "laboratory" indicates a concept verified by laboratory studies and initial hardware development.
in the equipment-testing stage, and a 4 Mta⁻¹ large-scale high-
temperature slurry bed industrial equipment is under construc-
tion.

3.1.3. Coal-to-SNG conversion

Several large-scale coal-to-methane plants are in service or
under construction in China. Most of these projects apply existing
gasification and methanation technologies. For example, crushed
cool pressurized gasification technology was applied in the Da-
tang Hexigten Banner project (4 × 10⁸ m³·a⁻¹), the Datang Fuxin
project (4 × 10⁶ m³·a⁻¹), and the China Kingho Ilı Kazak Autono-
mous Prefecture project (5.5 × 10⁶ m³·a⁻¹). In addition, an adiabat-
ics fixed-bed reactor has been widely used for the methanation
process in current approved projects.

Domestic research and development (R&D) in coal-to-SNG
conversion has been carried out recently. The Datang Interna-
tional Chemical Technology Research Institute Co., Ltd. has built
a methanation plant with a capacity of 3000 m³·h⁻¹ (SNG), and
has realized stable operation for more than 5000 h. The average
methane content of the products is 96.41% [29]. The methanation
catalyst that was developed has successfully gone through the
industrial sidetrack test. The Southwest Research and Design In-
corporation of Chemical Industry and the China National Offshore Oil
Corporation (CNOOC) Gas & Power Group Ltd. also jointly devel-
oped a methanation process. Their constructed 2000 m³·h⁻¹ plant
has been operated successfully. The Dalian Institute of Chemical
Physics (DICP) and the Northwest Research Institute of Chemical
Industry have also carried out research on methanation.

Water pollution is a serious challenge of the coal-to-SNG
industry. Wastewater emitted during coal gasification has a
complex composition, with high concentrations of recalcitrant
compounds and high toxicity [30]. Until now, wastewater treat-
ment technologies have mainly been developed by the municipal
wastewater treatment industry; however, specific technologies
for coal-to-SNG wastewater treatment are necessary. A pro-
ject titled “Coal Gasification Wastewater Treatment and Reuse
Technology” has been supported by the National High-tech R&D
Program. The activated coke adsorption and biological treatment
technologies developed in this project have been applied in the
Datang Hexigten Banner demonstration project [29]. Other path-
ways to reduce and reuse wastewater have been explored. For
example, the combination of crushed-coal pressurized gasifica-
tion and water-coal slurry gasification was proposed in the scheme
of the 4 × 10⁸Nm³·a⁻¹ coal-based SNG project in East Junggar, the
Xinjiang Uygur Autonomous Region. According to their scheme,
wastewater from the crushed-coal pressurized gasifier will be
treated and reused in the subsequent water-coal slurry gasifier [31].

3.1.4. Coal-to-chemicals conversion

Research into coal-to-olefin technology has been systemati-
cally conducted in China. DICP has developed a dimethyl ether/
methanol-to-olefin (DMTO) process. The first commercial unit
applying the DMTO process was successfully started in 2011,
with a capacity of 600 kt·a⁻¹. The DMTO-II demonstration unit
was built in 2014, and contained a 1.8 Mta⁻¹ methanol unit and a
700 kt·a⁻¹ coal-based olefins unit. The Sinopec methanol-to-olefin
(S-MTO) process was developed by the Sinopec Shanghai Re-
search Institute of Petrochemical Technology, and was applied by
the 600 kt·a⁻¹ plant of Sinopec Zhongyuan Petrochemical Co., Ltd.
in Henan, which started up successfully and produced qualified
polymer-grade ethylene and propylene products in 2011. Tsing-
hua University developed a coal-to-methanol-to-propylene (coal-
to-MTP) process called fluidized-bed methanol-to-propylene
(FMTP). Its industrial pilot test has been verified, based on a unit
with a capacity of 30 kt·a⁻¹. Considerable progress has been made
recently in direct-synthesis gas conversion to light olefins via the
Fischer-Tropsch synthesis (FTS). In addition, a new process that
enables selective conversion of syngas by a bifunctional catalyst
has been developed by DICP [32].

With regard to coal-to- aromatics technology, methanol ar-
omatization is being widely applied and researched. A fluidized-bed
methanol-to- aromatics (FMTA) process has been developed by
Tsinghua University. The first FMTA pilot plant, with a capacity
of 30 kt·a⁻¹ (methanol), was constructed and operated successfully,
and a 1 Mta⁻¹ FMTA industrial demonstration plant has been
planned. The Institute of Coal Chemistry of Chinese Academy of
Sciences and Sedin Engineering Co., Ltd. jointly developed the
fixed-bed methanol-to- aromatics (MTA) process. A demonstra-
tion project with a capacity of 100 kt·a⁻¹ has been successfully
built and operated. The Beijing University of Chemical Technology
and the Shanghai Research Institute of Petrochemical Technology
have also developed MTA technology.

With regard to coal-to-ethylene glycol technology, the Fujian
Institute of Research on the Structure of Matter developed a core
catalyst and successfully operated a demonstration plant with a
capacity of 20 kt·a⁻¹ in 2009. Since then, several commercial
demonstration plants have been built. ECUST also conducted re-
search in this field. After completing an assessment of the contin-
uous and stable operation of a 1000 t·a⁻¹ pilot plant in 2011, sev-
eral demonstration plants (with capacities greater than 100 kt·a⁻¹)
have been constructed. By the end of 2015, the total production
capacity of coal-to-ethylene glycol had reached 2.11 Mt·a⁻¹ [33].

3.1.5. Low-rank coal pyrolysis

Low-rank coals (lignite and subbituminous coal) are those
that have been subjected to the least metamorphic change during the
coal-forming process, thus retaining greater fractions of mois-
ture and volatile matter and containing less fixed carbon than the
high-rank bituminous and anthracite coals [34]. It has been
estimated that more than 55% of China’s proved coal reserves are
made up of subbituminous coal and lignite [35]. There are some
difficulties in low-rank coal utilization, such as increased difficul-
ties in transportation and storage. Therefore, upgrading and high-
ly developed technology such as liquefaction, gasification, and
pyrolysis of coal are needed to convert low-rank coals into highly
valuable products [36]. Several pilot and demonstration projects
with coal pyrolysis have been launched in China. The Dalian
University of Technology developed a kind of lignite solid heat
carrier pyrolysis process. Engineering testing of different kinds of
coal has been carried out. A so-called coal-topping process was
proposed by the Institute of Process Engineering. This integrated
multiprocess for obtaining a high yield of light liquid fractions and
gaseous products by flash pyrolysis was realized in a CFB system [37].
A 10 t·d⁻¹ pilot test was completed in 2014, and a 200 kt·a⁻¹
industrial demonstration is under design.

Thus far, problems still exist for low-rank coal pyrolysis tech-
nology, including poor economic efficiency, the difficulty in con-
 trolling the quality of tar, the previously mentioned difficulties
with wastewater treatment, and so on [38]. Further research into
the optimization of the pyrolysis process, reactor improvements,
ool processing, the comprehensive utilization of pyrolysis gas, and
oil-electric-heat poly-generation is still needed.

3.2. Future perspectives

Coal conversion technologies play an important role in the de-
veloping of alternative fuels or chemicals which will be needed to
act as substitutes for China’s rare oil resources. However, due to
falling oil prices in recent years, overall losses in the coal chemical industry have increased, the operating load has dropped, and construction progress on planned projects has slowed down [39]. It is projected that there are clear signs that the oil market is adjusting and will gradually rebalance in an outlook report of BP P.L.C. [40]. Petroleum and other liquid fuels will remain the largest source of energy in the world, at least until the year of 2040 [41]. Therefore, no matter what, most coal conversion technologies will likely continue to be regarded as a strategic reserve technology to be studied. Nevertheless, coal conversion should be further developed in order to make it more competitive. It is necessary to find better options to maximize conversion efficiency via low energy consumption, low water consumption, and a low pollution emission mode. Overall planning, technical studies, new technique development, and systematic optimization are needed [42].

One possible approach is to achieve technology upgrades via incremental innovation. As to most conversion technologies, the construction of larger equipment is considered to be a primary means to upgrade technology. Such upgrade will be helpful toward accumulating valuable experience and reliable data, and identifying new problems in science and engineering. Plans are in place for water-coal slurry gasifier with a capacity of 4 kt-d⁻¹, and pulverized coal pressurized gasifier with a capacity of 3 kt-d⁻¹. A direct liquefaction plant with a capacity of 2 Mt-a⁻¹ and a coal and oil co-processing plant with a capacity of 0.5–1 kt-a⁻¹ are also on the drawing board. In addition to the upgrading measures, the optimal integration of coal conversion with thermal power generation, oil refining, hydrogen production, biomass conversion, fuel cells, and other related energy technologies should be strengthened in order to achieve energy cascade utilization and material recycling.

Another possible approach could be to realize a fundamental change of technology via radical innovation. New principles, catalytic bases, chemical reaction pathways, reaction-oriented control methods, and mechanisms of the direct synthesis of olefins, aromatics, and special oxygen compounds from syngas need to be properly investigated. Fundamental research is needed on the reaction of free radicals in the process of coal pyrolysis and liquefaction, and on the relationship between liquid and gas products with the composition and molecular structure of primary coal resources. Some progress has recently been made. For example, as mentioned in Section 3.1.4, the newly developed bifunctional catalyst by DICP may permit the use of coal- and biomass-derived syngas with a low H₂/CO ratio to avoid high water consumption during the water-gas shift [32]. The advent of this new technology is worth looking forward to.

At the same time, water conservation and environmental protection must be seriously considered in the coal conversion process. Additional efforts to handle high-organic and high-salt wastewater should be taken to achieve zero-emission wastewater recycling [43]. New technologies and new materials are highly encouraged.

4. Pollution control in coal-fired power plants

Coal consumption has caused serious environmental problems in China, especially from the largest consumer—the coal-fired power plant, which contributed more than 17%, 38%, and 37% of national emissions of PM, SO₂, and NOₓ, respectively, in 2013 [44]. Therefore, emission control at coal-fired power plants has played an important role in clean coal technologies in China, as with efficiency promotion.

4.1. Current status

4.1.1. Policies and regulations

Regulations and pollution control policies are definitely causing reductions in pollutant emissions from thermal power plants. Since 2004, emission limits have become stricter (Table 2), accelerating the use of air pollution control devices (APCDs) and the installation and application of similar new technologies in most coal-fired power plants. For example, in accordance with the new emission standard that took effect in 2012, electrostatic precipitators (ESPs) and flue gas desulfurization (FGD) units were installed in most coal-fired power plants, and selective catalytic reduction (SCR) units were installed in 80% of coal-fired power plants by 2014 [45]. At the same time, a series of national and local policies were issued and implemented. In 2012, the central government supplied ¥1.09 billion CNY to support the 15 key cities included in the Air Pollution Control in Key Areas during 12th Five-Year Plan for the implementation of comprehensive improvements in coal-fired boilers. Another such policy is the on-grid tariff premium policy, which compensates coal-fired power plants with 15 CNY/(MW·h)⁻¹, 10 CNY/(MW·h)⁻¹, and 2 CNY/(MW·h)⁻¹ for the costs of desulfurization, denitration, and PM removal, respectively.

Due to stricter emission limits for coal-fired power plants, the total emissions of SO₂, NOₓ, and PM have continually decreased since 2006 (Fig. 3) [46], even though the electric output from coal-fired power plants increased from 2.4 × 10¹² kW·h⁻¹ in 2006–2014. In particular, due to a new emission standard issued in 2011, SO₂, NOₓ, and PM unit emissions declined rapidly from 2.3 gce-(kW·h)⁻¹, 2.8 gce-(kW·h)⁻¹, and 0.4 gce-(kW·h)⁻¹, respectively, in 2011 to 1.5 gce-(kW·h)⁻¹, 1.5 gce-(kW·h)⁻¹, and 0.2 gce-(kW·h)⁻¹, respectively, in 2014.

4.1.2. Desulfurization technologies

Flue gas desulfurization systems in coal-fired power plants can be categorized into four types: wet scrubbers, spray dry scrubbers, sorbent injection, and regenerable processes, according to the specific chemical reactions and flow conditions [47]. Among these, wet flue gas desulfurization (WFGD) technology has become the most-used technology around the world because of its cheap and abundant solid sulfur agent, easy-to-use byproduct, adaptability to a wide range of coal, and possibility of greatly reducing engineering costs [48].

Due to increased use of FGD, the thermal power share of total SO₂ emissions decreased from 62.7% in 2005 to 38.4% in 2014 [49]. The greater reduction in SO₂ emissions per electric output found in the later years (Fig. 3) is mainly due to the following factors:

1) FGD operation and removal efficiency improved in response to the relevant emission standard (GB 13223–2011) and
to the Upgrade and transformation plan for energy saving and emission reduction in coal-fired power plants (2014–2020) that was published later (Table 2). Related technologies for improving the efficiency of WFGD can be divided into three categories. The first category aims to enlarge the resident time for the SO2 reaction; examples include using a dual spraying cycle in one absorber tower, or having two absorber towers in one WFGD system. The second category aims to improve the gas-liquid mixing process; examples include installing tray or cyclone technologies in the inlet of the spraying level in the absorber tower. The third category aims to improve the liquid drop removal efficiency of the humidity eliminators installed in the spraying layer, which simultaneously remove the fine particles entrained to the absorber. The efficiency of humidity eliminators also affects the removal of fine particles in the absorber, where the fine particle capture efficiency of liquid droplets is controlled by inertial impaction and thermophoresis, based on the temperature gradient and on the droplet Stokes number and diameter in the wet scrubbing absorber [50].

(2) The energy efficiency of the coal-fired power industry was increased in order to reduce fuel consumption and pollutant emissions, based on policies that shut off low-efficiency power plants with capacities less than 200 MW in 2007 [45] and that installed new ultra-supercritical units. In 2005, units sized at less than 300 MW accounted for more than 50% of the total coal-fired power plant capacity. This proportion was reduced to 25% by the end of 2012, while the proportion of units sized 600 MW and over rose to 40.15% [51].

The production of flue gas desulfurization gypsum (FGDG), the byproduct of wet and semi-dry desulfurization processes, has been increasing rapidly in China. The estimated production in 2010 was around 0.85 Gt, with less than 30% being reused. FGDG has a variety of beneficial applications; for example, it can be used as a cement retarder agent instead of natural gypsum; as feedstock in cement production; as a raw material in concrete products, gypsum powder, and grout; as an ingredient in waste stabilization; as a fill material for structural applications and embankments; and as raw material for wallboard manufacturing [52].

Another important use of FGDG is as an alkali soil amendment; as a fill material for structural applications and em-...
Thus, LNB-SCR technology is the dominant method of denitrification used in thermal power plants to meet limits of less than 50 mg·Nm\(^{-3}\). This combination can simultaneously achieve good technical and economic benefits.

When flue gas flows through a V-W-Ti catalyst, the vanadium (V) component is active in the oxidation of SO\(_2\) to SO\(_3\) [56]. The subsequent reaction with water (H\(_2\)O), and ammonia (NH\(_3\)) to form ammonium sulfate ((NH\(_4\))\(_2\)SO\(_4\)) or bisulfate (NH\(_4\)HSO\(_4\)) causes blockage of the air-preheater inlet and acid corrosion of the downstream equipment, and also increases PM\(_{2.5}\) emissions to a concentration of 2.5 mg·Nm\(^{-3}\) in flue gas [57].

### 4.1.4. PM control technologies

Due to health and environmental concerns, the formation and control of fine PM pollution, especially PM\(_{1.0}\), have been widely studied in China. Mechanisms of PM formation and some control methods. Ultratine PM formation can be reduced at an early stage of the pulverized coal combustion of high-sodium lignite and anthracite coal in a down-fired Hencken flat-flame, with the help of some advanced technologies developed by Tsinghua University [61,62]. These technologies include novel in situ low-intensity phase-selective laser-induced breakdown spectroscopy (PS-LIBS), an in-flame two-stage diluted sampling system, and a thermophoretic sampling system. Using a time-scale analysis approach, three characteristic times of the minimum mean diameter of primary particles (7 ms, 10 ms, and 21 ms), the initial increment point of particle-phase sodium, and the maximum devolatilization have been found to be highly correlated [63].

During the char combustion stage, temperature-driven condensation, inherent minerals shedding, and collision-aggregation on the surface of char dominate the intermediate mode particles, such that the char properties significantly affect fine particle formation [59]. Controlled by the vaporization-nucleation-condensation and solid-gas-solid processes, the yield of PM\(_{1.0}\) from lignite combustion is 1.6 times than char combustion, and is 5–8 times from the co-combustion of lignite and char in a 25 kW sustained down-fired combustor (Fig. 5) [64]. Li et al. [65] used the semi-coke briquettes that are commonly used for direct household use (cooking and heating). The average emission factors of primary PM\(_{2.5}\), elemental carbon, organic carbon, and carbon monoxide for the tested semi-coke briquettes were reduced by about 92%, 98%, 91%, and 34%, respectively, compared with those of the 20 raw coals tested [65]. Progress with the injection of high-temperature sorbents, such as kaolinite, lime, silica, and alumina, into the flame zone was made by Si et al. from the Huazhong University of Science and Technology (HUST) [66]. The results show that sodium aluminosilicate plays an important role in PM\(_{2.5}\) reduction by kaolin, due to the interaction between the metals and particles at the submicron size; the sorbents transform the particles from submicron size to supermicron size. In post-combustion control, sulfation, phosphonation, and nitratation will also affect the distribution of fine particles. Due to abundant phosphate content in municipal sewage sludge (MSS), the phosphonation of inorganic matter during the cooling of flue gas from the co-combustion of MSS with coal obviously reduces the mass concentration of fine particles [67].

Besides formation control during coal combustion, an effective method of reducing fine PM is ash removal from the flue gas from the furnace. However, the removal efficiency is lower than 90% for fine particles, which are between 0.1 µm and 1.0 µm in size when using traditional ESP and a bag filter [68]. To meet the new emission standards, a series of technologies have been researched and developed. Fig. 6 shows the general control strategies for fine particles from coal-fired power plants. When the flue gas temperature gets below 130 °C to 90 °C, the PM\(_{2.5}\) removal efficiency increases from 95.9% to 97.5%, due to the lower specific resistance of fly ash, and to reduced flow. Wet ESP is normally installed after the FGD system; it greatly reduces PM\(_{2.5}\), and can also reduce the emission of SO\(_x\) mist, mercury (Hg), and other heavy metals [72].

### 4.1.5. Demercuration technologies

Coal contains a variety of trace heavy metal elements including Hg, plumbum (Pb), arsenic (As), cadmium (Cd), cobalt (Co), nickel (Ni), and so forth. In Chinese coal, the concentration of Hg is 0.15–0.22 µg·kg\(^{-1}\). More than 99% of the Hg in coal is released from the combustion furnace into flue gas, in the form of gaseous Hg\(^0\) [73]. As a result, the effective control of Hg\(^0\) emission from coal-fired power plants has become the main technologies and researches for recent years. Two approaches can be used to effectively remove Hg\(^0\). One is injecting strong Hg oxidizer, such as halogens and ozone, into the system to transform Hg\(^0\) to Hg\(^2+\).

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**Fig. 4.** Formation mechanism and control methods of fine particles during coal combustion [59].
which can then be removed by wet FGD which exhibits efficiencies ranging from 40% to 90%. If SCR units are installed, the capture of Hg\(^{2+}\) in WFGD systems is increased up to 89% [74]. Another method is injecting effective sorbents to capture Hg\(^0\) [75].

APCDs in coal-fired power plants, such as SCR, ESP, WFGD, and wet ESP, have been found to be effective in removing most of the Hg\(^0\) (> 80%), due to the oxidation reaction catalyzed by SCR followed by capture in the WFGD or wet ESP. A series of field tests showed that the capture efficiencies of Hg\(^2+\) in ESP, bag filter, and WFGD were 29%, 67%, and 80%, respectively [73].

4.2. Future perspectives

The future development of pollution control technologies for coal-fired power plants may focus on the following topics.

(1) High-efficiency and low-cost control technologies are needed, such as joint control of pollutants and the industrial application of novel multi-field fine particle control technologies based on fundamental research.

(2) Control technologies for heavy metals and volatile organic compounds (VOCs) require more study and commercial application for the absorption and catalytic oxidation of VOCs and heavy metals such as Hg, As, selenium (Se), Pb, and so forth.

(3) Reuse of the byproducts of APCDs is an important issue. Examples include the utilization process for the byproducts of multi-pollutant removal and semi-dry desulfurization, and the regeneration of V-W-Ti catalysts.

5. Carbon capture, utilization, and storage

China accounts for more than 25% of global CO\(_2\) emissions, and CCUS technologies will play an important role in CO\(_2\) reduction in the future. Therefore, most of the research and demonstration projects for carbon capture and storage (CCS) have been implemented in recent years, and great progress has been made in the development of CCS technologies.

5.1. Current status

5.1.1. CO\(_2\) capture technologies

CO\(_2\) capture technologies can be categorized into three methods: pre-combustion capture, post-combustion capture, and oxy-fuel combustion, as shown in Fig. 7 [73]. Regarding pre-combustion technologies, the GreenGen IGCC project aims at capturing 2 Mt·a\(^{-1}\) of CO\(_2\) from a 400 MW IGCC power plant whose generating efficiency is expected to be 48.4%. Implementation of the project is intended to occur in three phases; after the completion of Phase 3, the CO\(_2\) that has been captured will be used in EOR. The commissioning of a 250 MW IGCC demonstration power station (Phase 1) was finished in 2011 [76].

Regarding post-combustion, three demonstration projects are in operation with scales of 3000, 100 000, and 10 000 t·a\(^{-1}\) (CO\(_2\)), respectively, as listed in Table 3. These demonstration projects show that post-combustion capture technologies are commercially available, mature technologies.

Fig. 8 shows the roadmap for oxy-fuel combustion technology R&D [77]. A 3 MWt pilot-scale oxy combustion boiler was put into commission at the end of 2011. It can capture 7000 t of CO\(_2\) per year, reducing the CO\(_2\) concentration from the boiler by 80%. A 35 MWt new-built oxy-fuel boiler was finished at the end of 2014. This system includes all the units in the oxy-fuel combustion boiler, such as the air separation unit (ASU), the boiler, and the CO\(_2\) compression and purification unit; thus, its operation will provide additional design and operating data and experience in oxy-fuel combustion. In addition, a long-term target has been set and a program will be launched to build new oxy-fuel boilers with capacities of 200–600 MW, after 2020.

5.1.2. CO\(_2\) transportation technologies

Transportation is the most technically mature step in CCS, and the pipeline is the most mature form of CO\(_2\) transport. The project team of EU-China Near Zero Emissions Coal found that the average cost of transportation was 12 yuan per 100 km·(t CO\(_2\))\(^{-1}\), or 26 yuan per 200 km·(t CO\(_2\))\(^{-1}\) [78]. China plans to complete 80 km of the supercritical pipeline project in 2015, 200 km in 2020, and not less than 1000 km in 2030 [79].

5.1.3. CO\(_2\) storage and utilization technologies

One of the major challenges in CCS is the issue of storage, which limits large-scale CCS operations at a global level, both in the short term and in the longer term. Table 4 shows the potential for the storage and utilization of CO\(_2\) in China [80]. There are 1.19 × 10\(^{11}\) t of CO\(_2\) storage in China's saline aquifers. Regarding utilization, China is projected to utilize almost 51 Mt·a\(^{-1}\) in 2020.
and 249 Mt·a⁻¹ in 2030 for CO₂ storage. However, this considerable potential would cover only a small portion of the CO₂ resulting from large-scale CO₂ capture from coal-fired power plants.

Shenhua’s 100 kt·a⁻¹ (CO₂) CCS demonstration project, which is currently in operation, is located in Ejin Horo Banner of Ordos City, the Inner Mongolia Autonomous Region. It is currently China’s first pilot project for deep salt/saline aquifer storage, as well as China’s first entirely coal-based CCS demonstration project. The CO₂ is captured from Shenhua’s direct coal liquefaction plant, which is located about 11 km west of the storage site.

China National Petroleum Corporation (CNPC) and Sinopec have successively launched CO₂-EOR campaigns in the oil fields of Jilin, Zhongyuan, Shengli, Jiangsu, Daqing, Changqing, and more, and have gained notable results. In addition, Yanchang Petroleum Group has scheduled and is implementing a long-term CO₂-EOR project (from 2010 to 2020). The project is supported by the US-China Clean Energy Research Center on Advanced Coal Technology Consortium (CERC-ACTC). In this program, 60 injection wells will be finished and 200–300 km of pipeline will be constructed before 2017; by the end of 2020, the CO₂ capture system will be finished for the full flow of CCS-EOR.

5.2. Future perspectives

CCUS technological development in China will focus on the following items:
(1) R&D of key issues for CO2 capture. These issues include fundamental research on flame speed and other combustion characteristics; ash formation and deposition; and the formation and control of pollutants under different conditions, such as oxygen pressure, coal types, and high-pressure CFB reactors.

The oxygen-carrier is the key factor in a CO2 capture chemical reaction loop. The structure and characteristics of the oxygen-carrier, the reaction mechanisms for different types of fuels, the regeneration mechanism, and recycling technologies are significant for further studies.

Types of new absorbers will be further studied and developed for high-efficiency and low-cost CO2 separation. Examples include raw materials and the manufacturing process for the industrial application of the sorbents.

(2) Technical and economic optimization of long-distance CO2 transport, based on the flow characteristics, erosion, and security of supercritical CO2.

(3) Further development of geological modeling, related devices, and monitoring systems for EOR and the coal-bed methane process. The demonstration operation of open-pond and tubular technologies for algae culture will be accomplished to develop key processes and to optimize the reactor and system.

Relevant mechanisms and the development of technologies for new and long-term CO2 utilization will be studied; these include CO2 mineralizers and chemical utilization for biodegradable polymer materials, alcohols, and hydrocarbons.

(4) Implementation of a demonstration of the whole CCUS process. This demonstration should implement CO2 capture, transport, and utilization or storage; it will help to further develop key devices, system optimization, and operation regulation, and to accelerate the commercial application.

6. Conclusions

Coal is the most abundant energy resource in China, and will continue to be the dominant energy source in China for decades. In order to better use coal, it should be developed in a sustainable manner. CCTs have achieved remarkable development during the past 10–15 years.

(1) In the field of coal-fired power generation technology, China has reached a new level in the past 10 years. The world’s largest ultra-supercritical power generation units have been developed and manufactured in China, and the world’s most advanced ultra-supercritical power generation units have been established here. Independent R&D of 600 MW air-cooling units has achieved great progress. A 250 MW IGCC demonstration power plant was completed and put into operation. A breakthrough was made with the 600 MW ultra-supercritical CFB boiler technology, which has been put into commercial operation.

(2) Quite a lot of coal conversion technologies have progressed rapidly in recent years from pilot scale to demonstration and commercial scales. To convert coal in a more efficient, economic, and environmental manner, radical innovations in new catalytic bases, chemical reaction pathways, reaction-oriented control methods, and mechanisms are needed.

(3) Due to progress in combustion and pollutant-control technologies, and to the driver of stricter emission standards and policies, the total emissions and unit emissions of SO2, NOx, and PM are continuously decreasing even though electricity output is rapidly increasing. Pollutant-control technologies play an important role in clean coal technologies.

(4) Demonstrations of CO2 capture, such as pre-combustion capture, post-combustion capture, and oxy-fuel combustion, and CO2 storage and utilization, such as saline aquifer storage, CO2-EOR, micro algae cultivation, and so forth, have been accomplished. The whole CCUS process will be demonstrated in the next few years, which will accelerate its commercial application in China.

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Compliance with ethics guidelines

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Nomenclature

APCD air pollution control device
ASU air separation unit
CCS carbon capture and storage
CCT clean coal technology
CCUS carbon capture, utilization, and storage
CERC-ACTC US-China Clean Energy Research Center on Advanced Coal Technology Consortium
CFB circulating fluidized bed
CNOOC China National Offshore Oil Corporation
CNPC China National Petroleum Corporation
CPU CO2 processing unit
DICP Dalian Institute of Chemical Physics
DMTO dimethylether/methanol-to-olefin
ECUST East China University of Science and Technology
EHE external heat exchanger
EOR enhanced oil recovery
EPRI Electric Power Research Institute
ESP electrostatic precipitator
EU European Union
FGC flue gas cleaning
FGD flue gas desulfurization
FGDG flue gas desulfurization gypsum
FMTA fluidized-bed methanol-to-aromatics
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