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Current status and technical challenges of CO_2 storage in coal seams and enhanced coalbed methane recovery: an overview

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Abstract In the past two decades, research on CO_2 storage in coal seams and simultaneously enhanced coalbed methane recovery (ECBM) has attracted a lot of attention due to its win–win effect between greenhouse gas (CO_2) emission reduction and coalbed methane recovery enhancement. This paper presents an overview on the current status of research on CO_2-ECBM in the past two decades, which involves CO_2 storage capacity evaluations, laboratory investigations, modelings and pilot tests. The current status shows that we have made great progress in the ECBM technology study, especially in the understanding of the ECBM mechanisms. However, there still have many technical challenges, such as the definition of unmineable coal seams for CO_2 storage capacity evaluation and storage site characterization, methods for CO_2 injectivity enhancement, etc. The low injectivity of coal seams and injectivity loss with CO_2 injection are the major technique challenges of ECBM. We also search several ways to promote the advancement of ECBM technology in the present stage, such as integrating ECBM with hydraulic fracturing, using a gas mixture instead of pure CO_2 for injection into coal seams and the application of ECBM to underground coal mines.

Keywords CO_2 storage in coal seams · ECBM · Permeability · Hydraulic fracture · Gas mixture

1 Introduction

Carbon dioxide (CO_2) is one of the main greenhouse gases which cause the global warming. A major source of anthropogenic CO_2 is the combustion of fossil fuels to generate electricity. Mitigation and controlling CO_2 emission are critical to address the greenhouse effect. CO_2 geological utilization and storage (CGUS) is believed to be an effective CO_2 emission reduction option (Xie et al. 2013). One of the CGUS technologies is to inject CO_2 into coal seams to displace CH_4. In the process, CH_4 can be utilized as a clean energy resource, and CO_2 can be stored in coalbed mainly by the mechanism of adsorption called CO_2-ECBM. The advantage of CO_2-ECBM over other CGUS options is that the value of CH_4 produced helps to alleviate partly or wholly the storage costs (Gale and Freund 2001). Therefore, in the past two decades, the research on CO_2-ECBM has attracted a lot of attention.

In this paper, we firstly present an overview of the current status of research on CO_2-ECBM in the past two decades, which involves CO_2 storage capacity evaluations, laboratory investigations, modelings and pilot tests; then some technical challenges of CO_2-ECBM are described; finally, we search several ways to promote the development of ECBM technology in the present stage.

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2 Current status of CO_2-ECBM

Due to the past two decades' study, great progresses have been made in ECBM technology, especially in evaluations of CO_2 storage capacity in coal seams, laboratory studies related to CO_2-ECBM mechanisms, modelings of CO_2-ECBM process and also we have conducted some pilot/demonstration tests.

Table 1 Some evaluation results of CO_2 storage capacity in coal seams

Scale	CO_2 storage capacity ($\times 10^9$t)			Reference
World				
	0 (low)	267 (best)	1,480 (high)	Hendriks et al. (2004)
	150			Stevens et al. (2001)
	3–15 (low)		200 (high)	Intergovernmental Panel on Climate Change (IPCC) (2005)
Europe				
	1.5			Vangkilde-Pedersen et al. (2009)
Country				
China	12.078			Liu et al. (2005)
	142.672			Yu et al. (2007)
	9.881			Fang and Li (2013a)
Netherlands	8			Hamelinck et al. (2000)
Japan	0.625			Yamazaki et al. (2006)
Coal basin/region				
San Juan	1.4			White et al. (2005)
Bowen	0.87			White et al. (2005)
Ordos	0.66			White et al. (2005)
Sydney	0.15			White et al. (2005)
Western Canada	0.17			White et al. (2005)

2.1 Evaluations of CO_2 storage capacity in coal seams

Much research has been done to develop and advance the coal seam CO_2 storage technology, especially storage capacity evaluation study. Previous studies have shown that there were large capacities of CO_2 storage in coal seams in the world (Intergovernmental Panel on Climate Change (IPCC) 2005; Gale and Freund 2001), countries (Liu et al. 2005), basins or regions (Bachu 2007; Kronimus et al. 2008; Vincent et al. 2011). Some evaluation results of CO_2 storage capacity in coal seams are presented in Table 1.

However, evaluations of CO_2 storage capacity in coal seams are uncertain due to insufficient data and previous evaluations are usually based on many assumptions (White et al. 2005). For example, in the capacity evaluation study, the so-called unmineable coalbeds usually refer to coalbeds at maximum buried depth of 800 or 1,000 m (Bachu 2007) or more shallow. But, with the development of technology, coals buried at this depth may eventually be mined in the future, and much of the capacities will go unused.

2.2 Laboratory studies related to CO_2-ECBM

Laboratory studies related to CO_2-ECBM focus mainly on multicomponent gas competitive adsorption, supercritical CO_2 adsorption, adsorption induced coal swelling and its influence on coal permeability and injectivity.

2.2.1 Multicomponent gas competitive adsorption

Researchers generally believe that the adsorption of each component in gas mixture is not independent, and there are competitions among different gases. Binary gas adsorption isotherm is always between the isotherms of high adsorption capacity gas and low adsorption capacity gas. Different gas compositions can result in different isotherms. Multicomponent gas isotherm is more complex due to gas compositions affected (Krooss et al. 2002). Zhang et al. (2005) reported that there was a significant difference between multicomponent gas adsorption and pure gas adsorption, but the isotherms matched the Langmuir equation for both gas mixture and pure gas. (Mazumder et al. 2006) studied the adsorption characteristics of pure CO_2 and flue gas. Busch et al. (2003) investigated the preferential adsorption of characteristics of CH_4 and CO_2 on coal under high pressure (25 MPa) condition. Their results showed that CH_4 at low pressure was easier to be adsorbed than CO_2, but at pressure above 5 MPa, CO_2 was more affinitive to coal than CH_4. Fitzgerald et al. (2005) measured the isotherms of CH_4, N_2, CO_2 and the binary and ternary mixture. Gruszkiewicz et al. (2009) studied the sorption kinetics of CO_2, CH_4 and their proportional mixture.

2.2.2 Adsorption induced coal swelling

Adsorption of CO_2 may induce coal matrix swelling. This results in the reduction of permeability and injectvity which had been observed by field test (Reeves 2004). Therefore, the investigation on coal swelling induced by CO_2 adsorption is very important. Day et al. (2008) observed the coal swelling at high pressure CO_2 atmosphere by the optical method. Mazumder and Wolf (2008) measured the swelling of the coal in CO_2-ECBM experiment, and studied the effects of CO_2 injection on coal porosity and permeability theoretically. Goodman et al. (2006) studied the structural changes of unconstrained powdered coal contacted with CO_2. Romanov and Soong (2008) studied the differences between block sample swelling and powdered sample swelling with CO_2 absorbed. Their results showed that CO_2 adsorption on block coal caused 7 % expansion and the swelling rate of powdered sample was 8 %. Fang and Li (2012) studied coal swelling under stress condition by adsorption of CO_2, N_2

and CH_4, respectively. Romanov et al. (2006) investigated the influences of CO_2 adsorption induced coal swelling on the adsorption capacity measurement.

2.2.3 Influences of gas injection on coal permeability and injectivity

Under reservoir conditions, the sorption-induced coal matrix swelling may affect the flow characteristics of gas in coal, such as coal permeability and injectivity. Coal permeability is an important parameter related to the coalbed methane (CBM) production and the ECBM operation. Therefore, it is significant to investigate the influences of gas injection on coal permeability. Guo et al. (2008) investigated the permeability changes during CBM and ECBM process in the laboratory. Fang and Li (2012) and (Fang et al. 2013) studied coal permeability changes with different gas adsorption. Lin et al. (2007) studied the relationship among coal absolute permeability, pore pressure and gas components. Durucan et al. (2008) simultaneously measured gas adsorption or desorption induced coal train and permeability changes. Han et al. (2008) measured coal permeability and breakthrough pressure of N_2 and CO_2 by single-phase and two-phase flow and adsorption experiments. Shi et al. (2008) investigated CO_2–CH_4 convection–diffusion phenomena in a coal matrix. Viete and Ranjith (2006) investigated the CO_2 adsorption influences on coal compression strength and permeability under uniaxial and triaxial condition.

2.3 Modelings of CO_2-ECBM

CO_2 storage in coal seams and enhanced coalbed methane is actually a multi-physics process coupled with competitive adsorption/desorption, diffusion and gas–water multiphase flow.

2.3.1 Multicomponent adsorption theory

Numerous studies show that CH_4 and other gases adsorption on coal are monolayers physical adsorption, and the isotherms fit well with Langmuir model. For multicomponent gas system in ECBM process, extended Langmuir model is usually used to describe the competitive adsorption characteristics (Sun 2004).

2.3.2 Diffusion theory

Gas migration on coal matrix is generally believed to be driven by diffusion (Thimons and Kissell 1973; Gray 1987a, 1987b). In the process of gas injection into coal, convection–diffusion exists between injected gas in cleats and CH_4 in matrix. With this mechanism, CH_4 is displaced by injected gas.

2.3.3 Flow theory

Fluid flow in coal is a process combining multicomponent gas, water and coal. The simulation model should consider multicomponent gas adsorption/desorption, diffusion, sorption-induced coal swelling which induces permeability change, and the interaction between flow field and stress field. Ozdemir (2004, 2009) established a CO_2–CH_4-water flow model to simulate the process of CO_2 storage in coal seams and enhanced coalbed methane recovery by Athena Visual programming package. Ozdemir's model did not consider the sorption-induced swelling. Manik (1999) developed a two-phase flow composition model to simulate the ECBM process. His model included multicomponent gas and water. Seto et al. (2006) established a four components (CO_2, N_2, CH_4, H_2O) model for CO_2 storage in coal seams and ECBM simulation. Fang (2009) developed a multiphase flow-solid coupled model to simulate the ECBM process.

2.3.4 ECBM simulator

Existing CBM numerical simulators which are developed for the primary CBM recovery process have many important features considered, such as: (1) a dual porosity system, (2) Darcy flow in the natural fracture system, (3) pure gas diffusion and adsorption in the primary porosity system and (4) coal shrinkage due to gas desorption.

However, the process becomes more complex with CO_2 injection. Additional features have to be considered (Law et al. 2002), such as: (1) coal swelling due to CO_2 adsorption on coal, (2) mixed gas adsorption, (3) mixed gas diffusion and (4) non-isothermal effect for gas injection. Simulators currently widely used for ECBM simulation include some commercial simulators, such as GEM, ECLIPSE, SIMED II, COMET2 etc., and non-commercial simulators such as GCOMP and so on. Law et al. (2002) compared their features in detail. The features of the above simulators are shown in Table 2.

In addition to these popular simulators, some researchers have also developed their own simulators for ECBM simulation. METSIM2 is a three-dimension two-phase multicomponent simulator. The simulator takes into account the competitive adsorption of multicomponent gas mixture and the dynamic evolution model of coal seam permeability (Shi and Durucan 2005). Law (2003) also compared it with other simulators in his comparison study. U.S. Sandia Nationa Laboratory modified TOUGH2 for ECBM simulation (Sandia National Laboratories 2003). CBM-SIM, a specialized unconventional oil and gas reservoir simulation

Table 2 Features of main ECBM simulators

Features	Simulator				
	GEM	ECLIPSE	COMET	SIMED II	GCOMP
Multi-component gas	√	×	√	√	√
Dual porosity	√	√	√	√	×
Mixed gas diffusion	√	√	√	√	×
Mixed gas adsorption	√	×	√	√	√
Dynamic permeability and porosity	√	√	√	√	√
Coal swelling/shrinkage	√	×	√	√	√

software, was also used for CO_2/N_2-ECBM simulation. The IPARS-CO_2 Parallel Thermal Compositional Simulator developed by The University of Texas at Austin can also be used for ECBM simulation. Syahrial and Lemigas (2005) developed a simulator named LEMIGAS to simulate ECBM and CO_2 sequestration in coal.

2.4 CO_2-ECBM pilot/demonstration tests

From the 1990s to date, more than ten ECBM pilot/demonstration tests have been conducted in the world (as shown in Table 3). They are mainly operated in United States, Canada, Poland, Japan and China. Every tests are described in detail as follow:

2.4.1 ECBM pilot/demonstration tests in United States

2.4.1.1 Allison unit project The Allison Unit project is the first and the largest CO_2-ECBM pilot test in the world (Reeves and Oudinot 2004). There are four CO_2 injection wells and nine CH_4 production wells in this project. Formerly, the nine wells had been produced using conventional pressure-depletion methods for more than five years. CO_2 injection began at 1995. After almost five years of injection, about 277 kt CO_2 had been injected. Due to CO_2 injection, the CH_4 recovery ratio had been enhanced by 150 % was up to 95 %.

2.4.1.2 Tanquary well project The Tanquary test was designed to determine the CO_2 storage capacity, injection rate and the ECBM recovery potential of Illinois Basin coal. The pilot's injection formation was the Springfield coal, high volatile bituminous rank, thickness 7 ft, depth 900 ft, desorbed gas content ranged 150–210 cf/ton (dmmf) primarily methane (MGSC web 2013). A four-well design, consisting of an injection well and three monitoring wells, was developed and implemented, based on numerical modeling and permeability estimates from literatures and field data. Injection of CO_2 gas took place from June 25, 2008 to January 13, 2009. A "continuous" injection period ran from July 21, 2008 to December 23, 2008, but the injection was suspended several times during this period due to equipment failures and other interruptions. Approximately 102 tons of CO_2 was injected over the duration of the project. Monitoring results showed that there was no CO_2 leakage into groundwater or CO_2 escape at the surface (Finley and Moulton 2012).

Table 3 ECBM pilot/demonstration test projects in the world

Project name	Country	Location	Project/injection start time	Total CO_2 injected (t)	Coal depth(m)
Allison unit project	America	New Mexico	–/1995	277,000	950
Tanquary well project	America	Southeastern Illinois	–/2008	91	273
Lignite CCS project	America	Western North Dakota	2007/–	80	500
Northern Appalachian basin field test	America	West Virginia	2003/–	20,000 (planned)	550
Central Appalachian coal seam project	America	Southwestern Virginia	–/2009	907	490–670
Black Warrior Basin coal seam project	America	Alabama	–/–	252	460–470
Pump Canyon CO_2-ECBM/sequestration demonstration	America	New Mexico	–/2009	16,700	910
ARC ECBM project	Canada	Alberta	–/–	200	
CSEMP	Canada	Alberta	–/–	10,000	
RECOPOL	Poland	Kaniow	2001/–	760	1,050–1,090
Qinshui Basin ECBM project	China	Qinshui Basin	2004/–	192	478
Yubari project	Japan	Ishikari coal basin	–/2004	884	890
APP CO_2-ECBM project	China	Liulin	–/2011	460	560
Huaneng deep coal seams CO_2-ECBM demonstration project	China	Qinshui Basin	2014/–	1,000 (planned)	>1,000

2.4.1.3 Lignite CCS project In 2007, the Plains CO_2 Reduction (PCOR) Partnership initiated a field-based test in Burke County in northwestern North Dakota to determine the fate of CO_2 injected into a representative lignite coal seam and to uncover the potential for ECBM production. Approximately 90 tons of CO_2 were injected over roughly a 2-week period into a 10–12-foot (3–4-m)-thick coal seam at a depth of 1,100 feet (335 m). CO_2 was injected through a single injection well, which was surrounded by four monitoring wells. These monitoring wells employed various technologies to track the presence and movement of CO_2 in the lignite coal seam. This validation test demonstrated the overall feasibility of injecting CO_2 into coal seams in the field scale. It was safely executed, suggesting that similar equipment could be deployed, and comparable operations could be successfully implemented at other field sites (U.S. DOE 2013).

2.4.1.4 Northern Appalachian basin field test CONSOL's northern Appalachian basin field test involved two coal beds, the Pittsburgh and Upper Freeport coals in a 200-acre area of Mars hall County, West Virginia. The project began in 2003 and was completed in 2010. This demonstration project planned to test horizontal drilling for carbon storage with ECBM recovery. Horizontal drilling will maximize drainage of CBM and minimize the surface footprint of the injection operation. Horizontal drilling may also limit the negative impacts of coal swelling that might limit injectivity of a single, vertical well. As much as 20,000 tons of CO_2 would be injected over the two-year period, or until CO_2 breaks through to the production well (Greb et al. 2010). No report about the final injection quantity was found.

2.4.1.5 Central Appalachian coal seam test The Southeast Regional Carbon Sequestration Partnership (SECARB) planned two coal injection tests as part of their Phase II research (Greb et al. 2010). One was conducted in the central Appalachian basin in southwestern Virginia. For the field validation test, an existing coalbed methane (CBM) well was converted for CO_2 injection. The initial injection of 45 tons of CO_2 was completed on January 10, 2009. In total, 1,000 tons (U.S. short tons) of CO_2 were injected into the interval at an average rate of 41.6 tons per day. The maximum rate was 54.6 tons/day, but injectivity decreased to 20 tons/day.

2.4.1.6 Black Warrior Basin coal seam project The other coal injection test led by SECARB was conducted in the Black Warrior Basin in the southern Appalachians. The principal objectives of the SECARB Black Warrior coal test are (1) to determine if sequestration of carbon dioxide in mature coalbed methane reservoirs is a safe and effective method to mitigate greenhouse gas emissions and (2) to determine if sufficient injectivity exists to drive CO_2-enhanced coalbed methane recovery efficiently. This program will help develop strategies for CO_2 injection into multiplecoal seams with a broad range of reservoir properties. Coal seams in the Black Creek, Mary Lee, and Pratt coal zones of the Pennsylvanian-age Pottsville Formation were selected for the injection test. A total of 252 tons of CO_2 were injected to three coal seams (SECARB web 2013).

2.4.1.7 Pump Canyon CO_2-ECBM/sequestration demonstration The Pump Canyon CO_2-enhanced coalbed methane (CO_2/ECBM) sequestration demonstration project was planned to demonstrate the effectiveness of CO_2 sequestration in a deep, unmineable coalbed at the Pump Canyon site in the San Juan Basin of northern New Mexico via a small-scale geologic sequestration project (which, though termed small-scale, is the largest volume of CO_2 injected into a coalbed to date). A total of 167 kt of CO_2 was injected in about a 12-month period (July 30, 2008 to August 12, 2009) (Grigg et al. 2012).

2.4.2 ECBM pilot/demonstration tests in Canada

2.4.2.1 ARC ECBM project The Alberta Research Council, Inc. (ARC) of Alberta, Canada, developed a pilot site at the Fenn Big Valley, with two main objectives: (i) to reduce greenhouse gas (GHG) emissions by subsurface injection of CO_2 into deep coalbeds, and (ii) to enhance CBM recovery factors and production rates as a result of CO_2 injection (Gunter 2009). The overall program was divided into five phases:

(1) The proof of concept study-initial assessment and feasibility study of injecting carbon dioxide, nitrogen and flue gases into the low permeability bituminous Mannville coals of Alberta.
(2) The design and implementation of a CO_2 micro-pilot test following Amoco Production Company procedures.
(3) The design and implementation of flue gas ($CO_2 + N_2$) micro-pilot tests.
(4) Source-sink matching, simulator improvements and economic assessment model.
(5) Extension of micro-pilots to lower rank bituminous and higher rank anthracitic coals.

Pure CO_2, pure N_2 and flue gas (consisting of 13 % CO_2 and 87 % N_2) were considered to be injected in this project. Early results indicated that the flue gas injection seems to enhance methane production to a greater degree than that possible with CO_2 alone, because of the different roles of the two gases while sequestering CO_2. As a result, a total of 200 tons of CO_2 were injected.

2.4.2.2 CSEMP project CSEMP stands for CO_2 sequestration and enhanced coalbed methane production pilot. The project and research program were led by Suncor Energy Inc. and Alberta Research Council, respectively. The overall scientific/technical objective of the project was to extend the pilot to test coal seam response to CO_2 injection, determine the CO_2 storage parameters, evaluate ECBM production potential and establish storage, monitor and verify the parameters and evaluate the impact on ground water or ground water production. The CSEMP project was a multi-well pilot with one injection well and two production wells. During the pilot, two CO_2 injection-falloff cycles were conducted. A total of 10,000 tons of CO_2 were injected (Deng et al. 2008).

2.4.3 ECBM pilot/demonstration tests in EU

2.4.3.1 RECOPOL project European Union (EU) initiated an ECBM pilot test named RECOPOL (Reduction of CO_2 Emissions by Means of CO_2 Storage in the Silesian coal basin of Poland) in Poland. The RECOPOL project, started in November 2001, was the first European field demonstration of ECBM. The main objective of the RECOPOL project is to demonstrate that CO_2 injection in coal is a feasible option under European conditions and CO_2 storage in coal layers is a safe and permanent solution. The RECOPOL site is located in the west central Upper Silesian basin in the South of Poland near the Czech border. Liquid CO_2 from an industrial source was first injected in August 2004. Continuous injection started in April 2005, after reservoir stimulation. The total CO_2 injection was 760 t, with 68 t CO_2 produced back (van Bergen 2007). Although CO_2 injection ended in June 2005, the pilot is still ongoing. Currently, the focus is on monitoring and verification (Wageningen and Maas 2007).

2.4.4 ECBM pilot/demonstration tests in Japan

2.4.4.1 Yubari project The Yubari project is Japan's first CO_2-ECBM field trial which had been designed to evaluate technical and economic feasibility of extracting methane gas while storing CO_2 in Japanese coal seams. The project located near the town of Yubari on the island of Hokkaido in northern Japan. It was two multi-wells micro-pilot test with an injection well and a production well. The test was carried out in the period between May 2004 and October 2007. There were a variety of tests conducted in the injection well, including an initial water-injection falloff test, series of CO_2 injection and falloff tests. It was believed that low injectivity of CO_2 was caused by the reduction in permeability induced by swelling in the coal matrix. So N_2 flooding test was performed in 2006, to evaluate the effectiveness of N_2 flooding on improving well injectivity. The N_2 flooding test showed that daily CO_2 injection rate was boosted, but only temporary (Fujioka et al. 2008). Throughout the project, a total of 884 tons of CO_2 were injected (Fujioka 2008a).

2.4.5 ECBM pilot/demonstration tests in China

2.4.5.1 Qinshui Basin ECBM project A single well micro-pilot ECBM test was designed for the south Qinshui site as part of a Canada/China bilateral project. The micro-pilot approach for coalbed reservoir evaluation has three primary goals. The first goal is to measure the data accurately while CO_2 injecting into and producing from a single well. The second goal is to evaluate the measured data to obtain estimations of reservoir properties and sorption behavior. The third goal is to use calibrated simulation models to predict the behavior of a larger scale pilot project or full field development.

The micro-pilot was designed in six stages as follows:

(1) Inspection of wellhead equipment.
(2) Solation of the No.3 coal seam from the No.15 coal seam and installing additional downhole and surface equipment.
(3) Initial production testing to determine baseline reservoir properties.
(4) Intermittent injection of CO_2 for up to 30 days followed by a 30-day shut-in period.
(5) Production testing after the CO_2 injection period.
(6) The final shut-in test.

Before the injection of CO_2, the well was put on production for 134 days starting on October 28, 2003 and a set of baseline data were collected. Injection of CO_2 started on April 6, 2004. Liquid CO_2 was injected at an injection pressure, which was less than the fracturing pressure of approximately 8 MPa. 192 t CO_2 was successfully injected into No.3 coal seam through 13 injection cycles, each cycle based on injecting one truck load of CO_2. Each injection cycle was a daily cycle of injection and soak. CO_2 injection was completed on April 18. The well was shut-in for an extended soak period of about 40 days to allow the CO_2 to come to equilibrium with the coal. The well was placed on production from June 22, 2004 for 30 days. The production rates and gas composition data were used to estimate the sorption behaviour and to calibrate a reservoir simulator to predict the behaviour of full-scale pilots and full-field development. A final shut-in test was carried out to estimate the reservoir properties and near-well conditions (Wong et al. 2007).

2.4.5.2 APP CO_2-ECBM project AAP CO_2-ECBM project is a collaborative project between China United Coalbed

Methane Corp. (CUCBM) and Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia and supported by JCOAL, Japan. The project was operated at Liulin gas block, Lvliang city, Shanxi province by CUCBM. In this project, a multi-lateral coal seam well was used for CO_2 injection. CO_2 injection was commenced in September 2011 and completed in March 2012. This was the first field trial in the world to inject CO_2 into multi-lateral horizontal well in coal seams. Over 460 tons of CO_2 was injected into a multi-lateral horizontal well. Using horizontal well helps to increase CO_2 injectivity compared with vertical wells (Pan 2012).

2.4.5.3 Huaneng deep coal seams CO_2-ECBM demonstration project Just recently, the Ministry of Science and Technology for the People's Republic of China (MOST) plans to fund a deep coal seams CO_2-ECBM demonstration project. The project is led by Huaneng Clean Energy Research Institute, and will be started in 2014. The main purposes of the project are to demonstrate the technology of CO_2 storage in deep coal seams in Qinshui Basin and to simultaneously enhance the coalbed methane recovery. 1,000 tons of CO_2 is planned to be injected during this project. This will be the largest ECBM project in China.

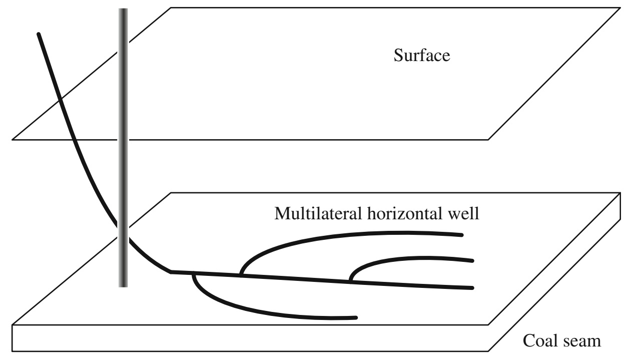

Fig. 1 Layout of well pattern of multilateral horizontal well for ECBM operation (After Pan 2012)

3 Technical challenges of CO_2-ECBM

Despite so much progresses mentioned above, we still face great technical challenges to implement the large-scale commercial development of CO_2-ECBM. Some of the technical challenges are described as follow:

3.1 Definition of unmineable coal seams for CO_2 storage capacity evaluation and storage site characterization

For the purpose of CO_2 emission reduction, CO_2 must be stored in coal permanently, the coal seams used for storing CO_2 should be unmineable forever, otherwise, coal mining, combustion, or gasification would release CO_2 stored in the coal. The definition of unmineable coal is crucial for capacity evaluation and storage site characterization. However, universally accepted quantitative definition of unmineable coal seams does not yet exist. Coal that is considered unmineable because of geologic, technological, and economic factors (typically too deep, too thin, or lacking the internal continuity to be economically mined with today's technologies) may have potential for CO_2 storage (U.S. DOE 2012). In many capacity evaluation literatures, unmineable coal seams usually refer to coal seams at maximum buried depth of 800 or 1,000 m (Bachu 2007). DOE's Big Sky Carbon Sequestration Partnership (BSCSP) and Plains CO_2 Reduction (PCOR) Partnership define coal as unmineable if it is beneath at least 305 m of overburden. DOE's Midwest Geological Sequestration Consortium (MGSC) adds two considerations to their definition: all coals shallower than 152 m are mineable and so are unsuitable for CO_2 sequestration, and at 152–305 m deep, coal seams 0.5–1.1 m thick are unmineable and so are reasonable sequestration targets (U.S. DOE 2010). (Fang and Li 2013a) defined coal seams buried at the depth of 1,000–2,000 m in China as unmineable coal seams for CO_2 storage capacity evaluation.

Changes in technology and economics over time shift the threshold of unmineability and therefore complicate attempts to quantify this resource. We need a generally accepted definition of unmineable coal in order to develop a methodology to assess the storage potential in unmineable coal seams, and to characterize potential coal seams for CO_2 storage (Corum et al. 2013).

3.2 Method for CO_2 injectivity enhancement

Successful injection of CO_2 into coal seams requires sufficient permeability along pores and fractures, yet adsorption of CO_2 reduces permeability due to swelling of the coal. Permeability and injectivity reduction had been encountered in several field pilot/demonstration, such as Allison Unit project, Qinshui Basin ECBM project and Yubari project. For CO_2 storage in coals or ECBM recovery projects operation, effective injectivity enhancing technology should exist. Horizontal well or multilateral horizontal well as used in APP CO_2-ECBM project (as shown in Fig. 1) may be an effective way to increase CO_2 injectivity compared with conventional vertical wells.

3.3 Other challenges

Other challenges include some common issues the same as other CGUS technologies, such as security, stability, economy, environmental risk, etc., are not detailed in this article.

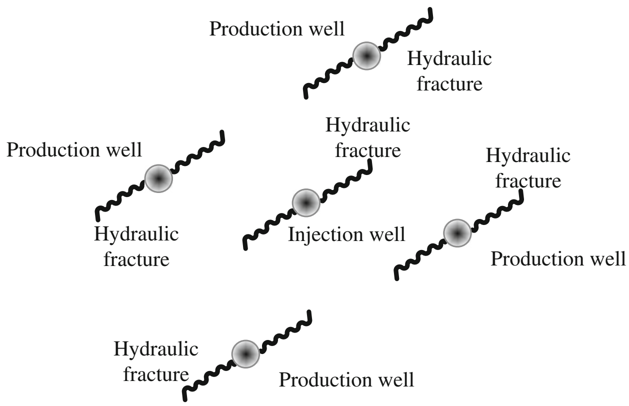

Fig. 2 5-spot pattern configuration of the hydraulic fracturing wells for ECBM operation

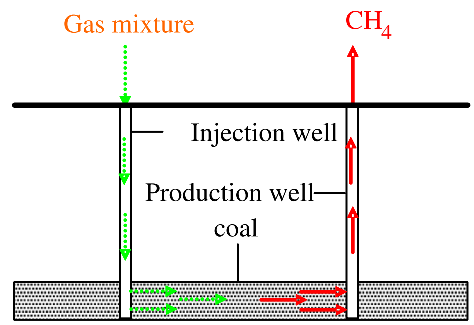

Fig. 3 Schematic diagram of G-ECBM technology (After Fang and Li 2013b)

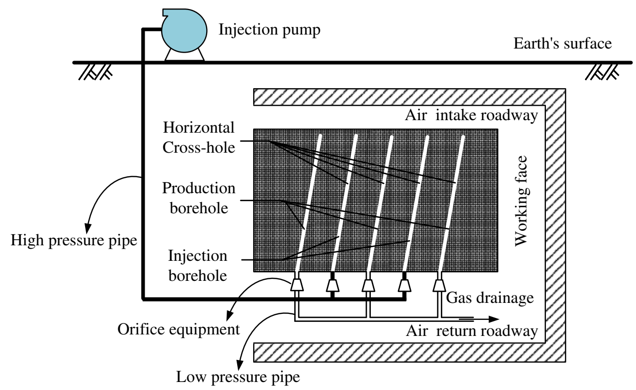

Fig. 4 Typical layout for an underground ECBM system (Fang and Li 2013b)

4 Prospects of CO_2-ECBM

Taking into account the state of the art and the technical challenges of ECBM technology, other applications of ECBM mechanisms may be feasible and significant to promote the advancement of ECBM technology at the present stage. The following ideas may be good choices for this purpose.

4.1 Integrating ECBM with hydraulic fracturing

Hydraulic fracturing treatment is an effective way to enhance coal permeability, thus CO_2 injectivity. Therefore, if we use hydraulic fracturing wells as the injection and/or production wells, and put reasonable configuration, we may get an excellent effect on CO_2 injectivity. Figure 2 shows a typical 5-spot pattern configuration of the hydraulic fracturing wells for ECBM operation.

4.2 Gas mixture instead of pure CO_2 for injection into coal seams (G-ECBM)

As revealed in the field pilots in Japan and Canada, comparing with pure CO_2, N_2 injection into coal seams can induce coal matrix shrinkage and results in width of micro-fracture in coal, and thus increase permeability and injectivity to some extent. So it is beneficial to inject CO_2 mixed with N_2 into coal. In other words, gas mixture, consisting of rich N_2, some CO_2 and/or other gases, instead of pure CO_2 is injected into the coal seams through injection wells to displace the methane from coals and drive it to the production wells. This process is called gas mixture enhanced coalbed methane (G-ECBM) recovery (Fang and Li 2013b). The concept of G-ECBM is shown in Fig. 3.

4.3 Application of ECBM to underground coal mines

Different from CO_2-ECBM, which aims at CO_2 storage as well as enhancement of CBM recovery from unminable coal, the objective of ECBM applied to underground coal mines is to enhance the CBM recovery ratio from minable coal and thereby decrease the risk of gas outburst while mining. Thus underground ECBM can significantly reduce mine downtime due to improved gassy mine conditions and safer mining environments, provide an opportunity to utilize more CBM and reduce GHG (methane) emissions (Fang and Li 2013b). A feasible underground ECBM system is typically illustrated in Fig. 4.

Application of ECBM to underground coal mines do not store or reduce any CO_2, and has no contribution to GHG mitigation. However, we can investigate some the same key technical issues with CO_2-ECBM, such as regulation and control technology of gas injection, factors affecting the components of a gas mixture and so on.

5 Conclusions

CO_2 storage in coal seams and enhanced coalbed methane recovery (CO_2-ECBM), one of the CGUS options, has been paid special attention in the past two decades due to its win–win effect on simultaneously storing large volumes of CO_2 in unmineable coal seams permanently and enhancing coalbed methane recovery ratio, which can offset some of the costs associated with CO_2 storage. In this article, we give an overview of research status of ECBM from capacity evaluations, laboratory investigations, modelings and pilot tests. There is no doubt that we have made great progress in CO_2-ECBM research in the past two decades. However, we still face a lot of technical challenges, such as the definition of unmineable coal seams for CO_2 storage capacity evaluation and site characterization, methods to enhance CO_2 injectivity, security, and economy and so on. Finally, we describe several possible ways to promote the development of ECBM technology in the present stage including integrating ECBM with hydraulic fracturing, using a gas mixture instead of pure CO_2 for injection into coal seams, application of ECBM to underground coal mines.

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