Integrated development of coal fuels

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Coal is the major source of energy in India. Optimal utilization of coal and associated fuels will improve energy security. Integrated development of coal fuels is discussed in the article. Integration of coal fuels with petroleum exploration and development activities is essential. Integrated development of coal fuels will improve project economic and help in pollution control. It would be a desirable step towards conservation of major energy source.

Keywords: Coal bed methane, coal fuels, coal gasification, coal production.

COAL is one of the world's most important sources of energy. It fuels almost 40% of electricity worldwide. Coal has been the world's fastest growing energy source in recent years, with growth faster than those of gas, oil, nuclear, hydro and renewables[1]. It has provided fuel for electricity, cement production and other industrial activities.

It has been estimated that there are over 1001 billion tonnes (bt) of proven coal reserves the world over, occurring in 70 countries, with major reserves in USA (270 bt), Russia (170 bt), China (130 bt), India (92 bt) and Australia (85 bt)[2]. At current production levels, proven coal reserves are estimated to last about 200 years. In contrast, proven oil and gas reserves are equivalent to around 41 and 67 years respectively. Over 68% of oil and 67% of gas reserves are concentrated in the Middle East and Russia[3].

Minimizing the risk of disruptions to energy supplies is an ever-important issue. They are caused by accident, political intervention, terrorism or industrial disputes. Coal has a strategic role to play at a time when we are increasingly confronted with issues relating to energy security. Coal is a crucial and secure fuel source for many countries.

The Indian scene

Coal mining in India was started in 1774 in West Bengal. In 1947, coal production was 30 million tonnes (mt) per year and coal mining operations were primarily in the private sector, till 1971–73. The entire coal industry in India was nationalized[4] during 1972–73. It was followed by massive investments by the Government of India in this sector. India now ranks as the third largest coal producer in the world, next only to China and USA. China and USA produced 1956 and 933 mt respectively, during 2004. India produced 373 mt in the same year[5]. Indian hard coal offers fuel source to domestic energy market for many decades.

As a result of exploration carried out down to a depth of 1200 m by the Geological Survey of India (GSI) and other agencies, a cumulative total of 246 bt of hard coal resources has been estimated in the country as on 1 January 2004. About 92 bt is recoverable by conventional mining up to the depth of 300 m. Coal occurs in sedimentary rocks of Gondwana Formations of Permian age in peninsular India and younger Tertiary formations of the northern/northeastern hilly region. The Gondwana Formation contains 245 bt, while the tertiary sequence holds 907 mt of hard coal[5]. Coal deposits, spread over 27 major coalfields, are mainly confined to the eastern and south-central parts of the country. Major coal deposits are in Jharkhand, Orissa, Chhattisgarh, West Bengal, Madhya Pradesh, Andhra Pradesh and Maharashtra. Table 1 provides definitions of some common terms used in the context of coal mining.

The reserves mentioned above do not include coal occurring in petroliferous Cambay basin Gujarat and Barmer area, Rajasthan. Here coal is encountered at the depth range of 500–1500 m. It is spread over Kalol and Sobhasan

Table 1. Definition of some common terms used in the context of coal mining

Resource: The amount of coal that may be present in a deposit or coalfield is defined as resource. This does not take into account the economic viability of coal mining. Not all resources are recoverable using current technology.
Reserves: These can be defined as proved, indicated and inferred reserves. Based on exploration results, where the boreholes are placed 1–2 km apart, coals are classified into the indicated or inferred category. Where boreholes are less than 400 m apart, the reserves are placed in the proved category.
Indicated reserves have been estimated with a lower degree of confidence than proved reserves. Inferred category has the lowest degree of confidence. These estimates are used for long-term planning.
Proved reserves: Reserves that are recoverable economically by current technology are considered to be proved. Proved reserves will therefore change according to the price of coal and technology.
Coal fuels: Coal, coal bed methane, coal mine methanol and underground coal gasification (see text for details).

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areas, north Gujarat. In Rajasthan, it occurs in Barmer and Sanchor areas. In the Cambay basin more than 4000 wells have been drilled for oil exploration and production. Many of these exploratory and development wells where coal had been encountered were dry and abandoned. It is imperative to combine petroleum activities with coal bed methane (CBM) and underground coal gasification (UCG) opportunities in this type of basin. Estimated coal is in excess of 63 bt in the Cambay basin[4]. Lignite reserves stand at around 36 bt, of which 87% occurs in Tamil Nadu and Puducherry[6]. Total lignite and Cambay-basin coal is 99 bt. Thus, total hard coal and lignite resources are 346 bt in the country.

Coal production

Coal production has achieved about 6% growth over the past 48 years in India. It had been slow and insufficient to keep pace with the demand. As a result, its share in the energy basket has slowly declined. India presently produces 390 mt of coal per year. It is grossly inadequate to meet demands even of existing power plants. Today power plants need to import 10 mt, which is expected rise to 80 mt by the end of the 11th plan (2011–12). Nationalized coal industry suffers from excess labour and huge inefficiencies. Reforms are long overdue in this sector. It needs to be thrown open to private and foreign investments for coal exploration and mining. This alone will meet the demand for the enormous quantities required to feed future needs and unleash potential benefits of energy security based on indigenous coal.

High prices of crude oil, hovering around US$ 60/barrel and alarming rising trend forecasts, are forcing energy planners and industry leaders of all major economic powers to look for non-oil based energy sources with urgency and concern. The Indian scenario is alarming, with 70% dependence on import of crude oil. Over-dependence on imported oil and gas adversely affects competitiveness of the Indian industry, sustainability and security. India has abundant coal reserves and it should logically form a cornerstone of energy planning and consumption pattern. Coal being the lowest-cost fuel for power generation, there is a need to derive economic benefit from its abundance. Economic development and poverty eradication depend on secure and affordable energy supply.

Coal bed methane

CBM is a natural gas found in coal beds. It was considered a nuisance because it created a variety of hazards during mining and was vented to the atmosphere. Such venting is now considered environmentally deleterious, as it is a potent greenhouse gas. It was a waste of useful fuel in the past. Nowadays, it is used for a variety of purposes ranging from domestic, commercial, industrial consumption to electrical power generation. Other gases that may co-exist in coal gas deposits in small quantities are ethane, propane, butane, carbon dioxide and nitrogen. One cubic metre of methane gas has a heating capacity of approximately 33,000 Btu (British thermal unit).

CBM is a clean fuel and easy to transport. It can be produced from abandoned and existing coal-mining operations. Opportunity also exists to exploit methane, which is still locked in the vast reserves of coal and coal measures that remain unutilized and are beyond conventional mining depths. CBM involves directly drilling into unworked coal and coal seams to release the methane locked within it. Methane gets released from coal by depressurization through pumping out water from the wells, which is completed in a target coal seam.

CBM formation

CBM is formed in two ways. During the early stage of coalification (the process that turns plant detritus into coal), biogenic methane is generated as a by-product of bacterial respiration. Aerobic bacteria (those that use oxygen in respiration) first metabolize any free oxygen left in the plant remains and the surrounding sediments. In freshwater environments, methane production begins immediately after oxygen is depleted. Species of anaerobic bacteria (those that do not use oxygen) then reduce carbon dioxide and produce methane through anaerobic respiration. When the temperature of coal during burial and lithification reaches about 50°C, and after an adequate amount of time, most of the biogenic methane is generated. At this stage, nearly two-thirds of the moisture gets removed and coal attains sub-bituminous rank.

When the temperature of coal exceeds 50°C due to the geothermal gradient during underground burial, thermogenic processes begin to generate additional CO_2, N_2, CH_4 and water. About this time, the amount of hydrocarbons or volatile matter increases and coal reaches bituminous rank. After the temperature exceeds 100°C, carbon dioxide production increases with little production of methane. Thermogenic production of methane does not exceed the production of carbon dioxide in highly volatile and high ranks of coal until the temperature is about 120°C. Maximum generation of methane in bituminous coal occurs at around 150°C. With progressive burial of coal, the coal rank increases and concurrently more CO_2 and methane are produced. CO_2 has a stronger affinity for coal than methane, but CO_2 is also soluble in water and therefore, its presence decreases as water is expelled out in the process of lithification of coal. Methane tends to get progressively concentrated with increasing rank. During coalification, more methane is generated than can be adsorbed and retained by coal. If coal was not exposed to low fluid pressures during its geological past, it should contain methane to its maximum methane-holding capacity.

One of the methods to classify coal is based on reflectance measurement. A polished slide of coal is used to find the reflectance parameter and this test allows identification of maceral content of coal. Macerals are micro-constituents of coal and are determined by the nature of the source material. There are three main types, viz. vitrinite from plant stems, liptinite from leaves, and inertinite from waxy material. Maceral composition of coal is an important parameter for methane adsorption and production. Vitrinite content is the most favourable constituent as it holds more methane and is characterized by development of best porosity amongst all macerals[7].

Porosity of coal is a key physical parameter. In porosity, coal dramatically differs from petroleum reservoirs. Coal contains macro-pores, transitional pores and molecular-size pores. Macro-pores are essentially cleats, a network of strongly developed longitudinal/face cleat and weakly developed orthogonal/butt cleat. These macro-fractures are ubiquitous and inherent to coal formation, where volume progressively decreases and fractures are generated. Coal has significant amount of micro-porosity. This gives rise to large surface area for adsorption of methane on coal. Methane molecules can get tightly packed in monolayers. Gas content as high as 600 cft/ton has been recorded in high-rank anthracite coal. The amount of methane adsorbed depends on temperature and pressure of the reservoir and nature of organic matter. Coal is said to be saturated when it holds maximum amount of methane, and reduction in reservoir pressure releases methane for production. Coal is under-saturated when pressure is required to be dropped below saturation pressure to release gas from the coal bed. Gas production takes place during pressure drop from saturation pressure to abandonment pressure in a well. Abandonment pressure is an economic limit of gas production and depends upon production rate, gas price and operational cost.

Development of CBM field

Reservoir engineering knowledge is essential to estimate CBM reserves and plan optimal development. Well spacing, location and orientation of horizontal wells, seam-wise distribution, production allocation in time and space, production profile and economic optimization are the main parameters for the development plan.

Understanding of a coal reservoir is a key aspect to produce methane at commercial rates. Flow of gas takes place through a cleat-network which has preferential directional element. Intrinsic permeability and reservoir pressure are the main components in controlling gas production. Reservoir pressure must be reduced below saturation pressure to initiate gas flow into a well bore. Gas is desorbed from micro-porosity in coal, closest to the cleat and a concentration gradient is established within the coal matrix, causing more methane to diffuse and flow into the well. Desorption time characterizes how long methane takes to travel through a coal particle to the cleat. In the cleat-network, gas together with water travels into the well-bore and follow Darcy law.

As a result, a well initially produces water. Progressively less water and more gas is produced. This is followed by a stable gas-production phase. During the gas-production stage, desorption controls the rate of production. In the final phase, gas production gradually declines as reservoir pressure approaches abandonment pressure[8].

Drilling, completion and production: Methane production is taken through a well, which is similar to the oil and gas wells drilled in the oil field. Drilling through coal presents a special challenge as coal permeability may be damaged during drilling and it may be difficult to restore it later. Choice of proper drilling fluid is crucial. Foam and air-drilling has been preferred in the industry.

Various types of completion are used in response to local requirements. These include mainly three types, viz. wells cased, cemented and perforated; single/multi-zone under-reamed open-hole cavity completion[9] and horizontal open hole.

Coal has inherent poor permeability and stimulation by hydro-fracturing forms an integral part of the well-completion practice. Hydraulic fracturing helps bypass well-bore damage, accelerates de-pressurizing, reduces fines production and improves production rates.

Surface gas handling facilities include gas–water separation, gas-gathering pipe lines, gas compression for transportation to end-user and water disposal.

Improved CBM recovery: The key elements are as follows.

(i) Development of horizontal drilling had enormous impact on increased oil production rates and enhanced oil recovery. This technology is a key input for better CBM recovery. Many horizontal wells have been already drilled in the oil and gas industry in India. Software and hardware to monitor the course of horizontal well and to guide drilling bit are important components of technology. Drilling contractors are available in the market to meet CBM requirements. Technology has been proven and tested. It would be advantageous to align horizontal wells orthogonal to face cleat-direction in coals.

(ii) CO_2 has stronger affinity to coal than methane. When CO_2 is injected in a coal bed, it would be adsorbed on the coal particle and in the process, methane would get released. This results in the twin benefit of CO_2 burial (sequestration) to reduce pollution and additional recovery of methane.

(iii) Hydro-fracturing in coal requires special skills, and proper designing of jobs is essential to obtain optimal results. It has been observed that generally the results of hydro-fracturing are erratic due to inadequacies in skills and design.

The world scenario

CBM is poised to develop into a booming industry in the US and UK. CBM formed 8% of the US gas production during 2002. Projects are under way in Ukraine, China and other developing countries to develop CBM as an energy source. The Coal Mine Safety Research Center in Hokkaido, northern Japan is trying to develop CBM as the new natural gas of the 21st century[1]. With the right investment, these projects will help solve the supply problems for these countries by converting CBM into a potential source of energy.

CBM development in India

CBM activities in India are under the Ministry of Petroleum and Natural Gas. The Government of India offered seven CBM blocks for exploitation[10], out which five were awarded and contracts were signed in 2002. Another three blocks were awarded on nomination basis. Total area covered by eight blocks is 2575 sq. km. Estimated in-place CBM potential is 393 billion cubic m. The blocks were awarded to ONGC, Coal India Ltd, Essar Oil, Reliance Industries, and Great Eastern Energy Corp.

ONGC drilled and tested the production potential at the Jharia Coal Field[11]. The well produced gas at an average rate of 12000 cubic m/day for a prolonged test period of 500 days.

Reliance Industries is reported to have drilled half a dozen wells in Sohagpur, Madhya Pradesh and confirmed commercial production rates of methane.

Assessment and development activities by various agencies are currently in progress in blocks awarded earlier. During the second round, nine blocks covering 5650 sq. km were offered in May 2003. Blocks in this second round contain 234 billion cubic m of in-place CBM potential. These were awarded to ONGC, Gujarat State Petroleum Company and Reliance. CBM activities are in the initial phase of commercial development.

In-place CBM resources in India were estimated to be 1534 billion cubic m by the Directorate of Hydrocarbons in 1999. Of these, 595 billion cubic m Permian coals of Gondwana and 939 billion cubic m in the Tertiary sequence. In-place CBM resource is estimated to be 2099 billion cubic m, with 1715 billion cubic m in Gondwana and 384 billion cubic m in the Tertiary sequence. Total recoverable CBM would be around 1049 billion cubic m with 50% recovery factor. Awarded blocks so far cover about 627 billion cubic m of in-place CBM potential, which is less than one-third of the total potential. Remaining areas are to be brought under production planning with the award of additional blocks and grant of unified license for coal–CBM–UCG/petroleum–CBM–UCG.

Coal mine methane from working mines

During underground coal-mining operations, methane gas is released and is required to be removed considering the safety of the miners. Occasionally methane causes explosion and fire. Mining operations involve breaking, crushing and fracturing of coal. Fresh air is supplied by blowers and vent-gases are released into the atmosphere. Vent-gases contain methane, which affects the environment adversely. Methane is considered a serious greenhouse gas because, kilogram for kilogram, it is 23 times more effective than carbon dioxide at trapping heat in the atmosphere. Methane is a short-lived greenhouse gas, with an atmospheric lifetime of about 12 years. Due to these properties, efforts are on to reduce methane emissions, which can result in rapid and significant positive effect on global warming. Now technology is available to generate electricity from vent-gases mixture with low methane content and to eliminate pollution[12]. Great strides have been made in the technology and methodology for extracting methane resource from active mines. The economic viability of recovering coal mine methane (CMM) is dependent on a number of parameters like type of coal, size of the deposit, rate of desorption and investment for drilling of wells and infrastructure. Vent-gases may often contain nitrogen, oxygen, CO_2 and water vapour along with methane, and it would be essential to do additional processing. Equipment is now available to transform a wide ranging concentration of methane (1–99%) for generation of electricity or injection into the gas-grid.

However, commercial exploitation of methane has the potential, now well proven, of harnessing the gas safely and beneficially to generate electricity and for additional benefits. A number of cases have occurred over the years, where mine-gas has migrated through disused mine entries or fissures in the strata into the surface. Uncontrolled danger and potential surface hazard to individuals and property is greatly reduced by CMM capture and utilization.

The advantages of utilization of CMM are: (a) Harmful ventilation to the atmosphere is reduced with significant reduction of greenhouse gas emission. (b) Electricity will be available to local users, especially in cases where former colliery sites are developed for industry and commerce. (c) Inward investment into coalfield community areas with developed technology will create jobs. It would be an acceptable development on the ground and would be welcomed by the community. A cost of a 10 MW CMM power-generating-plant is about £1.25 million in the UK[13].

CMM from abandoned mines

There are hundreds of thousands of acres of abandoned room-and-pillar mines which can be tapped for methane recovery. When these mines were abandoned, roughly 50% of the coal remained unrecovered. The rooms in these abandoned mines emit gases, which can be gainfully recovered. Gas from abandoned mines can provide an energy source, which would otherwise be a waste. CMM recovery from abandoned mines is a commercially viable proposition and such projects are in the operation in the coal sector in USA, UK, etc.

CMM potential in India is high. It is proposed to capture methane in working coal mines from mined-out areas and from abandoned mines, using vertical wells drilled from the surface. Methane is also produced by deep in-seam drilling of long horizontal wells in the coalface and surrounding strata. CMM production can also be achieved using the existing gob wells.

Typically any well or gob vent that coal miners have drilled is used for methane production. Gob-vent well is drilled in advance before mining, from the surface into the coal beds, to release methane gas and to avoid explosion. As the mine advances, gas is vented through the gob well. If the pressure is sufficient, gases are collected through a network of pipes. However, if the pressure is ambient, vacuum blowers are used to draw gases to the surface. Thus methane gas, which is a pollutant and a fire hazard, is converted into an energy source.

A facility using 3000 cubic m of coal mine gas, with 70% methane content can generate 300 kW of electric power. Internal combustion engines can adapt to generate electricity with CMM with 40% methane concentration. Gob-well gas may have methane content varying from 30 to 95% and heating value in range 10,500 to 28,000 Btu/m^3.

Underground coal gasification

UCG is a method of converting un-worked coal, deep underground, into a combustible gas which can be used for industrial heating, power generation or the manufacture of hydrogen, synthetic natural gas or other chemicals. The gas can be processed to remove CO_2, H_2S and NH_3 before it is passed onto end users, thereby providing a source of clean energy with minimal greenhouse gas emissions.

UCG technology can be applied after extraction of CBM from deeper coals that are not amenable for conventional mining operations. Integration of CBM and UCG activities is a key aspect in the rational development of coal-fuel resources. Unfortunately, this approach has so far not attracted the attention of the industry and other agencies.

The concept of gasifying coal underground and bringing the energy to the surface as a gas for subsequent use in power generation has received considerable attraction. UCG is the partial *in situ* combustion of a coal seam to produce a gas for use as an energy source. The process involves carbonization, distillation, cracking and combustion of by-products. The process may be represented in the following way.

$$C + O_2 \rightarrow CO_2 + \text{heat},$$

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat}.$$

If the hot gases remain in contact with unburnt coal, oxygen is further consumed by reducing reactions as below.

$$CO_2 + \text{heat} + C \rightarrow 2CO,$$

$$2H_2O + \text{heat} + C \rightarrow CO + H_2.$$

The reactions produce a gas mixture that is capable of burning as a fuel[3]. Calorific value may range from 800 to 1000 kcals/cubic m of gas[14].

Gasification is achieved by drilling two boreholes from the surface, one to supply oxygen and water/steam, and the other to bring the product-gas to the surface[9]. Technology of horizontal-well-drilling has improved production rates both in UCG and CBM operations. Use of directional drilling to drill in-seam wells in the coal bed has provided an effective method of coal access for UCG. In the past, problems have been accuracy, control and cost. Latest developments in down-hole motors and guidance systems, from the oil and gas exploration industry have now demonstrated improved accuracy and cost-effectiveness. Application of horizontal-well technology to coal seams (mainly for exploration and CBM) has taken place only in the 1990s, and the realization of its potential for UCG is only just beginning. UCG production through wells drilled from the surface has the added advantage to control the process parameters and in turn ignition and propagation of the UCG-front, ensuring safety of operational personnel. UCG produces a mixture of gases consisting of CO, CH_4, H_2, CO_2, N_2 and O_2 along with H_2S, NH_3, SO_2 and oxides of nitrogen. It is noteworthy that UCG produces fewer pollutants than direct burning of coal as fuel.

The erstwhile USSR had been producing fuel by UCG since 1930. Total UCG operations produced fuel equivalent of 300 MW. Till date, 15 mt tonnes of coal has been gasified to generate 50 billion cubic m of fuel gas. All early efforts did not have the benefit of horizontal wells. UCG has the advantage of combining the benefits of low cost of coal with efficient use and better pollution control.

Coal gasification, both on the surface and underground, is at the forefront of cleaner coal technology. UCG is a particularly suitable option for power generation. It has the same advantages as surface gasification of coal, and it also provides access to potential underground storage locations for CO_2 through wells drilled for UCG application. UCG also eliminates mining hazards.

The simplicity of UCG is attractive. However, application of the concept on large scale needs planning and background to drill horizontal wells, initiate ignition and maintain air/oxygen and steam supply.

It is clear from previous tests done in the industry that natural permeability of the coal seam to transmit gases to and from the combustion zone can be unreliable. For gasification over long distances in the coal seam, a properly constructed in-seam conduit should be developed before the coal seam is ignited and the gasification process is initiated. This conduit is possible by drilling a horizontal well in the required direction through thin coal seams.

The horizontal-well technology is being used regularly for degassing of coal seams in Australia, South Africa and the US. For the first time, in-seam coal wells can be constructed reliably and accurately, with much less risk of failure than previously encountered. Furthermore, the option of drilling gasification wells in much deeper coal seams, say over 1000 m, becomes possible. This has advantages in terms of cavity growth, power output and environmental benefits, including the possibility of CO_2 sequestration.

The potential for UCG in India relates to adding a new energy source, reducing environmental emissions, ensuring security and providing diversity of energy supply. UCG is partial *in situ* combustion (ISC) of coal. It is similar to ISC to enhance oil recovery of heavy oils. In both processes, partial combustion takes place. Both processes are sustained and propagated by supplying air/oxygen through an injection well. While steam and air/O_2 are injected in UCG, water and air/O_2 are supplied in ISC. The main difference is that coal has poor fracture porosity and permeability, while heavy-oil reservoirs have high intergranular porosity and permeability. It is therefore imperative to drill horizontal injection wells for successful propagation of UCG-front in the coal bed. Lack of horizontal-drilling technology was the key handicap for development of UCG in the past.

India has about 20 years of experience in successfully running ISC (enhanced oil recovery process) in the heavy oil belt of Mehasana, Gujarat. Incidentally this is the largest operation comprising 40 patterns in the world. It promises to enhance oil recovery from 7 to 40% of oil in place. ISC is being carried at depth of 1000 m. It may be mentioned that UCG trials in the world at around 1000 m depth are few. ISC application was done for the first time without any previous experience, which confirms the innovative potential available in the country. Background of ISC is an important factor to promote UCG activities in the country.

The benefits of UCG are the absence of waste tips and ash at the surface, elimination of surface plant for gasification and coal preparation, and availability of energy as a clean fuel gas. Furthermore, it provides access to the large-scale Indian coal deposits beyond conventional mining depths, which would otherwise not be exploited. This would include about 50% of Gondwana coals and 90% of Tertiary coals.

Granting unified license to coal miners to allow value-addition through CBM and UCG application, is necessary for rational integration and development of total potential. Segregation of these activities under coal and petroleum is not conducive for growth and national energy security. Similarly, in the basins of Gujarat and Assam where petroleum exploration and production are carried out, there is need to integrate with CBM and UCG production in Petroleum Exploration Licence (PEL) and Mining Licence (ML) areas.

UCG in abandoned coal mines

About 50% of coal is left behind in abandoned mines. Coal is in the form of pillars, and thin coal seams or steeply dipping coal seams are left behind by conventional mining operations. Abandoned galleries and wells are used for UCG operations. Attempts to produce UCG in this mode are done only in China and are still in the R&D stage. Technical uncertainties regarding process-control and the most important aspect of operational safety need to be resolved before commercial application.

Other aspects

Let us now consider a few other aspects.

CO_2 storage and retention (sequestration) and enhanced CBM recovery

A new, large, coal-fired power plant of 1000 MW capacity emits 6 mt of CO_2 annually (equivalent to emission of two million cars). It is estimated that in the past 252 years (1751–2002), 542 bt of CO_2 has been emitted by burning coal. It has been forecasted by the International Energy Agency that CO_2 emission from coal-fired power generating units would add 501 bt of CO_2 in just 23 years, i.e. during 2003–2030. Reduction of CO_2 pollution is a challenge and needs urgent attention. CO_2 is more concentrated compared to other gases, which makes it easier to capture and sequester/bury. Four such plants are under operation now, two in the US and two in Europe.

Conventional technology for separation of CO_2 from gas streams involves contact of gases with aqueous-amine solution in a tower. The amine selectively absorbs CO_2, and then it is transferred to another unit where it is heated, and CO_2 is released and separated. The amine is cooled, returned to the gas contact tower, and the cycle is repeated.

CO_2 can be separated from flue gases of the power plants and injected into coal beds where it would be adsorbed and simultaneously methane would get released. The results indicate that CO_2 is strongly adsorbed onto coal. However, adsorption behaviour of CO_2 changes with the rank of the coal. The mole ratio of CO_2/CH_4 adsorption varies from over 10 for low-rank coals to under 2 for medium and high-rank coals. The process has twin advantage of reducing pollution and increasing CBM recovery. Combining CO_2 sequestration in coal bed and enhancing CBM recovery makes the project economically attractive and environmentally desirable.

Sequestration of CO_2 and enhanced CBM recovery applies to a depth window defined by the range of pressure and temperature conditions over which CO_2 is in the gaseous state. It is important to project a depth tract into the phase diagram based on actual temperature and pressure gradients existing in a coal basin. This will indicate maximum depth for sequestration, which varies based on combinations of geothermal and pressure gradients, and is generally in the range of 500–900 m.

Field results from a R&D site located in New Mexico, USA are noteworthy. At Allison Field, CO_2 is being injected to recover methane. The study area consists of four CO_2 injector wells and 16 methane producers. The field originally began production in 1989, with CO_2 injection beginning in 1995. It was noted that for a period following commencement of CO_2 injection, methane production rate increased. The field was simulated and performance was matched by reservoir modelling. The study indicated that about 1.6 Bcf of incremental methane will be recovered as a result of injecting 6.3 Bcf of CO_2. Field studies demonstrate viability of improved methane recovery by CO_2 sequestration[12].

CO_2 sequestration might be achieved in conjunction with UCG. A UCG programme in a coal seam would leave behind highly porous cavities and stressed strata with fracture porosity[15]. As the partially burnt coal cools down, the abandoned cavities can be accessed by directional drilling or through the existing production wells. CO_2 would then be injected at high pressure for storage and retention. For permanent CO_2 sequestration, the depth and strata conditions must be suitable and need to be ascertained before the start of the project.

Integration of CBM and UCG activities

Extraction of CBM from greater depths (more than the conventional mining depth of 300 m) can be followed by coal gasification. For production of CBM, wells (preferably horizontal) are drilled and pressure in the reservoir is depleted. Hydro-fracturing is done in vertical wells to improve production rates and gas recovery. Depleted CBM production wells have less pressure and higher permeability around the well bore. Both these factors are advantageous for UCG application. In case of horizontal CBM well completion, it provides a better conduit for propagation of burning zone of UCG process. When the CBM well is vertical, hydro-fractures created for CBM production would form conduits for propagation of the UCG front. Most of the infrastructure, i.e. wells and surface facilities created for CBM production can be utilized for UCG. There is additional expenditure only for air/oxygen and steam injection. Integration will improve project economics with minimal investment.

Key inputs for CBM and UCG development

Development of horizontal drilling had enormous impact on increased oil production rate and enhanced oil recovery. This technology is the key input for better CBM recovery and also for UCG. Many horizontal wells have been already drilled in the oil and gas industry in India. Software and hardware to monitor the course of horizontal wells and to guide the drilling bit are important components of technology. Drilling contractors are available in the market to meet CBM and UCG demands. Technology is proven and tested.

Logging technology to identify coal bed, fractures, porosity and aquifers, is routinely used in the oil industry. Logging services are also available on demand.

Knowledge of reservoir engineering is essential to estimate CBM reserves and plan optimal development. Well-spacing, location and orientation of horizontal wells, seam-wise distribution, production allocation in time and space, production profile and economic optimization are the main ingredients of the development plan. Expert knowledge in this area is available due to 50 years of oil industry experience.

Twenty years of ISC background in the recovery of heavy oil would help in UCG application, as both processes are basically partial ISC in underground geological formation.

The key inputs for implementation of integrated programmes for the development of coal fuels are available in the country. Now efforts are required to coordinate expertise and resources from both the coal and oil sectors.

Integrated development of coal fuels

The total coal and lignite resources are about 346 bt. Of this, only 92 bt can be mined by conventional methods. The remaining 254 bt holds 2099 billion cubic m of in-place CBM and has the potential to produce 1049 billion cubic m of CBM (with 50% recovery factor). The CBM extraction phase can profitably be followed by UCG with available infrastructure of wells drilled for CBM. In-place potential of UCG is about 648,000 billion cubic m of coal and recoverable coal-gas would be around 324,000 billion cubic m (assuming 50% application). In addition, CMM can be captured from the working and abandoned coal mines.

It becomes apparent that untapped potential of total coal fuels is far greater than the present conventional approach, which allows partial development and utilization of the coal resources. The energy development plan needs to include all coal fuels to ensure optimal, and responsible use of natural resources, conservation, sustainability of development and energy security of the nation.

Indigenous content of coal fuels in the energy basket will ensure greater security and coal, due its abundance, will be a major contribution in future. In view of the rising and unsustainable import-bill of crude oil, focus on coal fuels will take a centre-stage sooner than expected.

There is need to promote awareness about integrated development of all coal fuels. Integrated development of coal, CBM, CMM and UCG can enhance project profitability and ensure rational utilization of non-renewable energy resource. Similarly, in the petroliferous basins, integrated development of petroleum, CBM and UCG is urgently required to optimize returns and provide energy source in power-deficient Gujarat.

Integrated coal fuels development will place the country at the forefront of technology, value-addition, energy security, pollution control through CO_2 sequestration and less emission of CH_4 into the environment, conservation of non-renewable resources and better returns on investment.

A large pit-head coal-based power plant in Orissa is expected to be established by Reliance Energy. Posco is planning a mega steel-plant in Orissa with coal as a fuel. This would generate a large amount of CO_2. These projects can integrate all concepts of developing and utilizing coal fuels to improve project profitability and reduce pollution.

Integrated coal fuels development concept

This concept has the following key components.

- CBM production prior to coal mining to reduce explosion hazards and de-water coal seam for safety. It also ensures utilization of methane as a energy source and reduction of greenhouse gas emission.
- Provides facilities to separate methane (CMM) from vent-gases in the working mines and integrate utilization.
- In case of pit-head power-generation plant, it separates CO_2 from stack gases and injects in coal beds in depth range of 500–900 m.
- Development of infrastructure of wells and surface facilities to produce CBM from coal deeper than 300 m in licensed areas.
- UCG applied after CBM operations to produce coal-gas utilizing wells drilled for CBM production.
- Produces CMM from abandoned mines to reduce emission and utilize methane energy source.
- Many of these activities are concurrent and can be integrated in time and space to match plant-life for optimal economic returns.

Policy initiatives for development coal fuels

It is imperative to frame a national policy to harness all coal fuels. The following actions will be required to achieve integrated development.

- Unified license for coal, CBM and UCG production along with CO_2 sequestration.
- Unified license for petroleum, CBM and UCG in those petroliferous basins where coal occurs.
- Incentives for CBM and UCG production as non-conventional energy source and for emission reduction. Policy options to promote CBM and UCG practised in UK, Australia and the US include market-based incentives, tax breaks, feed-in tariffs, direct grants/supports.
- Optimization of energy mix with dominant role for coal fuels.
- National awareness and focus, commensurate with the importance of energy security need to be created.
- Expediting the process of granting licenses for the remaining blocks for exploration of CBM and UCG.
- Supervisory agency to coordinate and promote integrated development of all coal fuels.

Conclusion

Coal fuels emerge as a cornerstone for energy planning because of the abundance of coal, it being the lowest cost fuel for power generation and other industrial uses. Coal fuels are available within the country and improve energy security. It is essential and rational to view all coal fuels together for planning and development. Isolated consideration of coal, CBM or UCG is sub-optimal and economically undesirable. Utilization of 92 bt of coal by conventional mining methods encompasses only a small part of the total resource potential, leaving a large portion of the energy resource locked-up. CBM production potential is 1049 billion cubic m (with 50% recovery factor) of clean fuel. Gas is easily transportable and there are no transit losses. UCG can unlock 324,000 billion cubic m (with 50% recovery factor) of coal-gas fuel. It is apparent that untapped potential of total coal fuels is far greater than the present conventional approach, which permits only partial development and utilization of coal resources. CO_2 sequestration/burial will significantly reduce pollution from pit-head plants and enhance CBM recovery. Integration of all these activities dramatically improves project economics, in addition to conservation of resources and reduction in pollution. Inputs for implementation of CBM and UCG activities are available within the country. Unified license needs to be provided to operators to integrate activities pertaining to all coal fuels in order to optimize project performance. Policy options to promote CBM and UCG practiced by UK, Australia and the US include market-based incentives, tax breaks, feed-in tariffs and direct grants/supports. National awareness and focus, commensurate with the importance of energy security, need to be created.

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Received 17 February 2006; revised accepted 20 December 2006