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Coal in the 21st Century: Electricity, Clean Environment and Advanced Materials

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Despite all the talk about the need for greater air pollution controls, about the rise of renewable energies, and even about global warming, there is little doubt that coal will remain an important energy source throughout much of the 21st century, especially so in the less developed nations. So, while the politicians and economists sort out their energy policies, the challenge for scientists and engineers in today's globalized economy is to devise suitable strategies for continued, but more profitable and environmentally friendlier uses of coals of varying rank and from different parts of the world. Clearly, pulverized coal combustion will remain important, but in a way that minimizes both the NO_x emissions and the fraction of unburned carbon, so that the ash can be converted to a higher-value-added product. Fluidized-bed combustion makes sense for high-sulfur coals, especially if gypsum can be commercialized. With its improved efficiency and elegant solution to conventional pollution, integrated gasification combined cycle technology has been surprisingly slow in gaining world-wide acceptance; perhaps the Kyoto Protocol will give it greater impetus. Finally, time is ripe for the emergence of a "coal complex", which combines an electric power plant with a coal "refinery". The coal refining part will be devoted not only to the generation of cleaner-burning fuels but also to the production of high-value-added solid carbon materials (e. g., for adsorbents, catalysts, batteries, supercapacitors, fuel cells), which not only greatly improve the economics of the overall enterprise, but help to solve some of the residual environmental problems of electricity generation by coal combustion.

Key words: *coal, combustion, environment, electricity, materials*

Introduction

In September 2004 the Russian government has agreed to sign the Kyoto Protocol. If ratified by the Russian Parliament, this means that international global warming legislation will soon become binding for its signatory countries [1]. There is no question that one of the most effective ways to reduce CO_2 emissions is to minimize the use of coal for electricity generation; after all, a simple mass and energy balance demonstrates that both oil and (especially) natural gas offer clear advantages in this regard (see fig. 1). But there is also no doubt that the world's abundant and relatively inexpensive coal reserves will continue to be used by many countries as their principal electricity-generating fuel, because of either economic or political realities and constraints. Under such circumstances, which are expected to persist throughout much of the 21st century, a new paradigm for the socially acceptable use of coal, in conjunction with the pressing need for electricity generation, is expected to emerge. It must include environmental friendliness, or at least minimal environmental impact, and new economic incentives, *e. g.*, in the form of higher-value-added products. Here an argument is presented that the concept of a vertically integrated *coal complex* embodies such a paradigm shift. Only a more effective collaboration of mechanical and chemical engineers, within the right economic incentives and favorable political climate, can make this happen.

Natural gas: $$\frac{80\,\text{kgC}}{100\,\text{kg}_{\text{ng}}}\,\frac{1\,\text{kg}_{\text{ng}}}{55000\,\text{kJ}}\,\frac{44\,\text{kgCO}_2}{12\,\text{kgC}} \quad 53\,\text{kgCO}_2$$

Residual oil: $$\frac{85\,\text{kgC}}{100\,\text{kg}_{\text{resid}}}\,\frac{1\,\text{kg}_{\text{resid}}}{46000\,\text{kJ}}\,\frac{44\,\text{kgCO}_2}{12\,\text{kgC}} \quad 68\,\text{kgCO}_2$$

Low-rank coal: $$\frac{65\,\text{kgC}}{100\,\text{kg}_{\text{coal}}}\,\frac{1\,\text{kg}_{\text{coal}}}{14000\,\text{kJ}}\,\frac{44\,\text{kgCO}_2}{12\,\text{kgC}} \quad 170\,\text{kgCO}_2$$

High-rank coal: $$\frac{85\,\text{kgC}}{100\,\text{kg}_{\text{coal}}}\,\frac{1\,\text{kg}_{\text{coal}}}{32000\,\text{kJ}}\,\frac{44\,\text{kgCO}_2}{12\,\text{kgC}} \quad 97\,\text{kgCO}_2$$

Figure 1. Order-of-magnitude comparison of CO_2 emissions from typical fossil fuels

Environmentally friendlier electricity generation

Figure 2 summarizes the key features of the currently most reasonable options for coal use in electricity generation. Pulverized coal combustion (PCC) is the most mature technology and it represents the overwhelming majority of electricity generating capacity in both the USA and the world in general. Because of such maturity, no significant improvements in its overall efficiency should be expected. Thus, for example, in the last ten years the average efficiency of U.S. power plants changed very little, as illustrated the tab. 1.

There are great expectations, plenty of opportunity and certainly much public pressure to make PCC electricity more environmentally friendly, especially in less developed nations. The technology exists, and the methodology has been developed to implement the relevant legislation. The costs are decreasing; even the economic benefits of cleaner air are now being quantified. These still depend on the opportunities for commercializing the by-products; for example, minimizing NO_x by burning fuel-richer must not be done at the expense of lower char burnout, which lowers efficiency and complicates ash

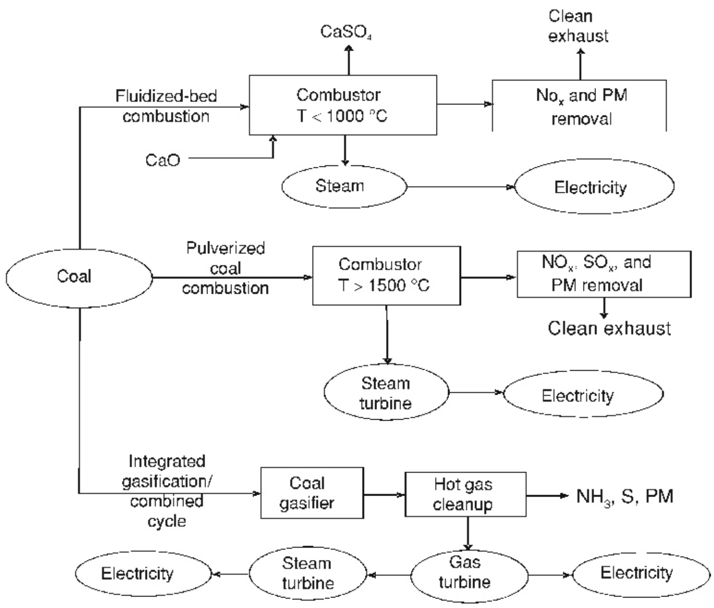

Figure 2. Commercially available options for coal use in electricity production

commercialization. Both mechanical and chemical process and project optimization, with early participation of scientists, engineers, economists and community leaders, is clearly the way to proceed.

Table 1.

www.eia.doe.gov	Tons coal	Average BTU/lb	MWh_t	MWh_e	Efficiency
1993	816 558 233	10315	4 936 695 596	1 642 055 280	0.333
1994	821 209 026	10338	4 975 883 417	1 639 862 531	0.330
1995	832 928 005	10248	5 002 954 298	1 657 958 730	0.331
1996	878 824 782	10263	5 286 358 093	1 742 765 712	0.330
1997	904 245 388	10275	5 445 629 465	1 793 150 334	0.329
1998	920 353 489	10241	5 524 296 547	1 823 018 900	0.330
1999	924 691 817	10163	5 508 062 943	1 832 066 627	0.333
2000	967 079 797	10115	5 733 346 008	1 910 575 307	0.333
2001	946 068 093	10025	5 558 872 737	1 851 823 368	0.333
2002	960 076 989	10157	5 715 463 659	1 881 204 797	0.329

Surprisingly, fluidized-bed combustion (FBC) technology [2] has not been as "popular" wih electric utilities (http://www.power-technology.com/projects/index.html) as might be expected based on its technical features: efficiency in excess of 40%, *i. e.*, higher than PCC and close to currently available integrated gasification combined cycle (IGCC), much lower SO_x and NO_x emissions than PCC. One of the few recent major projects is Liaoning Fuxin Gangue in China: the Shenyang Jinshan Thermoelectric Company is expected to install four 135 MW CFBC boilers.

Here is what an authoritative source [3] has to say about atmospheric FBC: "As circulating FBC (CFBC) plants have previously been limited to around 250 MW, they have not had the economy of scale to compete effectively with PCC units with flue gas desulfurization. At this size, they have found their niche in burning fuels not well suited to PCC applications, such as coal wastes and petroleum coke. However, now that 500 MW CFBC units are becoming available, they can generate electricity at a lower cost than a PC unit with flue gas desulphyrization (FGD) firing high-quality fuels with sulfur contents lower than 2%. At higher sulfur contents, the PCC unit with flue gas desylphurization (FGD) is more economical because it utilizes the sorbent more efficiently. Dry scrubbers have been added to the back-end of commercial CFBC units to improve sorbent utilization and lower the cost of electricity, and other means of improving sulfur capture have been identified for investigation. The dry scrubbers in conjunction with baghouses also capture hazardous air pollutants (HAPS), including mercury."

Pressurized FBC (PFBC) technology is still largely in its demonstration phase. Here is what a World Bank document [4] had to say about it some time ago: "Four PFBC plants are in operation (American Power Electric's Tidd in Ohio, ENDESA's Escatrón in Spain, Stockholm Energi's Vartan plant, and EPDC's 70 MW Wakamatsu plant in Japan); all utilize PFBC modules of approximately 70 MW_e. One demonstration plant is in the construction phase: Kyushu Electric's 350 MW K1 plant in Japan." According to the same source, the leading developer and supplier of PFBC technology is ABB Carbon, with a number of licensors, such as Babcock & Wilcox in the United States and Ishikawajima Heavy Industries (IHI) in Japan; other suppliers are Ahlstrom in Finland, Lurgi-Lentjes-Babcock in Germany, Ebara, Hitachi, and Mitsubishi in Japan. Indeed, ABB reported (www.abb.com) that it has built PFBC plants in Japan, Spain, Sweden, USA, and, more recently, a 74 MW_e plant in Germany. The Kyushu Karita plant is now in operation, and with its 360 MW capacity it is "the world's largest PFBC" [5].

The IGCC technology has been available commercially for at least a decade, but only the ones using natural gas instead of coal have been popular with electric utilities. (Arguably, they have been too popular, because the price of natural gas may rise substantially.) Both the Buggenum project [6], producing 253 MW from 2000 tonnes of coal per day at 43.2% efficiency, and the Puertollano project [7] in Europe are apparently successful demonstrations. The Sulcis project for Sardinia in Italy (5000 tonnes of coal/day) has been announced by Shell with a projected start-up date in 2006. In the USA there have also been several successful demonstration projects [8]. The American Electric Power company has now announced an ambitious plan for a 1000 MW plant. It is intriguing, however, that the many coal gasification projects in China are all oriented toward chemicals production rather than electricity generation. And there are several commercial-scale IGCC facilities (not using natural gas) – such as NPRC Negishi in Yokohama, Japan;

WMPI in Gilberton, Pennsylvania; Sarlux in Sarroc, Italy; and Wabash River in Indiana – that produce electricity using fuels other than coal (*e. g*., asphalt, waste coal, residual oil, or petroleum coke), and this offers even greater flexibility to future IGCC customers. An especially attractive feature of IGCC, in these times of impending adjustments to the Kyoto Protocol, is the much greater feasibility of CO_2 sequestration, at least from a technical standpoint, compared to either PCC or FBC. Apparently, however, acceptance by utilities of the "chemical" side of the process is among the major hurdles that need to be overcome.

Economically attractive coal utilization

Efficiency improvements

An important aspect of economic attraction of coal utilization in the coal complex of the 21st century is the improved efficiency offered, for example, by IGCC technology. Nevertheless, given the constraints imposed by the Kyoto Protocol and the anticipated complication with any high-throughput CO_2 sequestration technology, IGCC is not expected to be a panacea. Major improvements in the profitability of coal use, especially in regions where coal extraction is difficult (*e. g*., in deep underground mines) or expensive (*e. g*., due to high labor costs), must come from elsewhere. A *vertically integrated* coal complex, which produces advanced materials in addition to clean fuels and electricity, is the solution proposed here.

Advanced materials from coal

The flow diagram of the coal complex is presented in fig. 3. In addition to coal combustion, it exploits the virtues of coal pyrolysis, which focuses on the volatile products, as well as of coal carbonization, which focuses on the solid products. Its unifying theme is the optimization of surface properties of the coal-derived products, an issue intimately connected to coal surface reactivity. The underlying scientific concept is the *vertical integration* of its mutually related topics which make possible the optimization of each one of the steps leading to specific final products. Thus, for example, pyrolysis and carbonization represent the same process (heat treatment in the absence of a reactive atmosphere), which is of course the first step in the combustion process. Also, while the advanced adsorbents require an optimization only of their surface properties and therefore carbonization can be effected at low temperatures, the products devoted to electrocatalysis also require the optimization of electrical conductivity, and thus carbonization must be carried out at higher temperatures.

The technological concept that sustains the coal complex is that only an interdisciplinary approach can lead to a complete and optimized utilization of carbonaceous raw materials and to a maximization of the added value of all its products. Thus, for example,

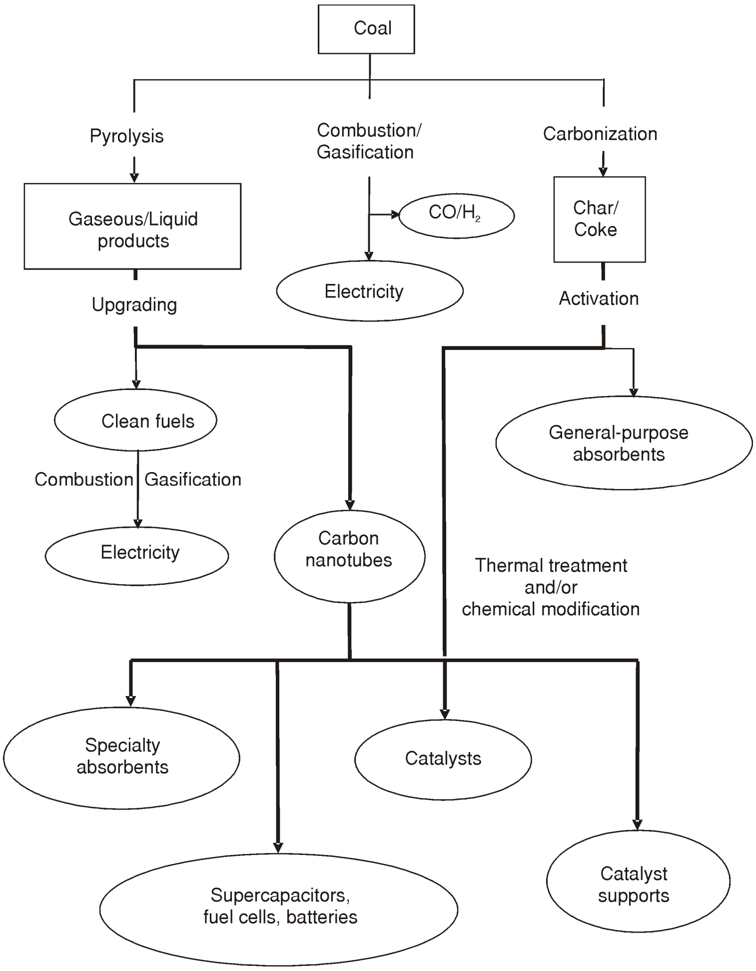

Figure 3. Flow diagram of a vertically integrated coal complex

the combustion of gases and liquids derived from coal is typically cleaner than that of its solid residue; but the economic viability of the process depends to a large extent on the fate of the solid residue, because it often represents more than 50% of the total product. If in each one of the steps in the production process it is kept in mind that the fate of the "residue" is not necessarily its combustion, and that it can be converted instead to a high-value-added *product* (*e. g.*, electrocatalyst support or bioadsorbent), the techno-economic feasibility of the entire process becomes much more attractive.

The proposed products of the coal complex reflect both technical and economic flexibility. When conditions allow it, straightforward combustion and/or gasification of coal is used to produce electricity and/or synthesis gas. When conditions demand it, increasing portions of the coal feedstock can be converted not only into cleaner gaseous or liquid fuels, but also to chars or cokes that in turn can be upgraded easily into specialty, high-value-added materials such as adsorbents tailored for selective removal of gas and water pollutants, or catalysts and catalyst supports for widely varying chemical or environmental industry applications. Thus, for example, chars rich in inorganic impurities are often excellent NO reducing agents and they can be used within the complex for NO_x control. An especially attractive and lucrative opportunity lies in the production of carbon-based supercapacitors, batteries or fuel cells. It is indeed interesting to note that such coal-based chemistry (carbochemistry) is emerging again as a complement to petrochemistry, especially for products that will be the basis of renewable energies of the mid- to late 21st century.

Conclusion

If the proposals outlined here are successfully converted into reality, it is expected that the coal complex will be in the 21st century what a petroleum refinery was in the 20th century: a showcase for the most advanced technologies, a powerful motor for innovation, a major source of employment and a highly profitable enterprise. Carbochemistry based on coal, which gave birth to the organic chemical industry in the 19th century, was replaced by petrochemistry in the 20th century, but it will resuscitate to become an important complement to petrochemistry in the 21st century. Under such a scenario, it may be possible to produce the huge amounts of electricity that modern societies demand without major disruptions to either the economy or the climate of the world. The likelihood that such a scenario will succeed is contingent on a much more effective collaboration, information transfer and understanding among scientists, engineers (especially mechanical and chemical engineers), economists and politicians. A truly interdisciplinary (rather than merely multidisciplinary) approach to the resolution of problems and the decision making processes will also be necessary.

References

[1] The most authoritative source is http://unfccc.int/resource/convkp.html (viewed 10/4/04).
[2] See, for example, http://www.netl.doe.gov/publications/factsheets/program/prog031.pdf
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[7] See, for example, http://www.gasification.org/Docs/2003_Papers/39IGNA.pdf
[8] See, for example, http://www.iea-coal.co.uk/site/database/cct%20databases/igcc.htm.

Апстракт

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Угаљ у двадесет првом веку: електрицитет, чиста околина и савремени материјали

Упркос много говора о томе како је потребно успоставити контролу аеро загађења, о већој употреби обновљивих извора енергије, као и глобалном загревању, не постоји ни мала сумња о томе да ће угаљ остати важан енергетски извор и кроз велики део 21-ог века, а првенствено код мање развијених земаља. Док политичари и економисти припремају нову енергетску политику, изазов за научнике и инжењере у данашњој глобализованој економији је да нађу одговарајућу стратегију за континуирано, али профитабилније и еколошки оправдано коришћење угља различитог квалитета у разним деловима света. Јасно је да ће сагоревање спрашеног угља остати најважнији вид његовог коришћења али кроз континуално смањење емисије NO_x и удела несагорелог угљеника, тако да се пепео може конвертовати у неки други вид високо вредних производа. Флуидизовани слој се чини добрим избором за сагоревање угља са високим уделом сумпора, а специјално у случајевима када се може спрегнути са производњом комерцијалног гипса. Упркос побољшаном степену корисности и технолошким предностима, технологије са интегрисаном гасификацијом у комбинованом циклусу за производњу електричне енергије и топлоте се изненађујуће споро прихватају у светским оквирима, уз очекивања да ће примена Кјото протокола поново актуелизовати увођење ове технологије. На корак смо од концепта „угљеног комплекса” који комбинује постројење за производњу електричне енергије и „рафинерију” угља, који ће у себи обједињавати системе за производњу чистијих енергената из угља као и високо вредне угљеничне материјале (на пример: абсорбенте, катализаторе, батерије, суперпроводнике, гориве ћелије), и који ће веома значајно унапредити економику самог производног процеса али и решити многе еколошке проблеме производње електричне енергије из процеса сагоревања угља.

Кључне речи: *угаљ, сагоревање, животна средина, електрична енергија, материјали*

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