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Opportunities for High-Efficiency Electricity Generation Inclusive of CO_2 Capture

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Abstract

Three basic options for advanced power plants, allowing energy conversion inclusive of CO_2 capture, are discussed: the semi-closed gas turbine cycle with atmospheric base pressure, the integrated gassifier/combined cycle with pressurised absorption of CO_2, and the supercritical semi-closed CO_2/H_2O cycle with liquid CO_2 capture. The merits of the different options are discussed and compared, and improvements to the basic layouts are proposed. The results show that all three solutions have a good potential for application, depending on the size of the plant and on the near or medium-term future perspective.

Keywords: gas turbines, semi-closed cycles, gassification, CO_2 sequestration, green house effect

1. Framework

The reduction of greenhouse effects puts requirements for a substantial improvement in energy conversion and utilisation technologies. The goals prescribed by the Kyoto protocol are presently addressed in developed countries improving the efficiency of energy conversion; however, it is very likely that this may prove to be insufficient in a very short time, so that other measures will probably be necessary.

Within the possible options, CO_2 sequestration with disposal in the deep seas or oceans, or in exhausted gas or oil wells, is one of the most mature technologies, which is already being used in some pilot installations (Kongsjorden, 1998; Eliasson, 1998).

CO_2 sequestration, from a more general point of view, can also be seen as the first phase of the transition to a clean fuel technology, represented in its ultimate development by substitution of current fossil fuels with environmentally-friendly Hydrogen. In fact, presently the most economic way of producing Hydrogen is still transformation of natural fuels, as an alternative to water hydrolysis. CO_2 sequestration can thus be seen as a transformation of fossil fuels into hydrogen, taking place at the power plant itself – which solves many of the technical, safety and economic problems of distributing hydrogen as a fuel.

2. Final Disposal of CO_2

CO_2 can be captured at a power plant site either as a gas (typically at low temperature and atmospheric pressure) or as a liquid (at supercritical pressure, p > 77 bar, and ambient temperature).

Depending on the technology used for carbon sequestration, the energy expenditure - under the form of low-grade heat, which can be often recovered within the power plant at the price of a small reduction in performance - can vary between 2 and more than 5 MJ/kg_{CO2}. If CO_2 is captured as a gas at atmospheric pressure, then the minimum (reversible) work for its liquefaction amounts at 232 kJ/kg; in practice, a multistage (3 to 4 stages) compressor with intercooling is needed, which at present technological levels implies an energy expenditure in the range of 300 to 400 kJ/kg.

After reduction in liquefied state, CO_2 must be transported (typically by trucks) and injected at high depth in the sea or in exhausted gas or oil wells. The extra energy consumption for this process can be considered a small fraction of that needed for the compression work (Langeland and Wilhelmsen, 1993).

It is thus easy to recognise that application of CO_2 separation at top-ranking present combined cycles, scoring efficiencies slightly

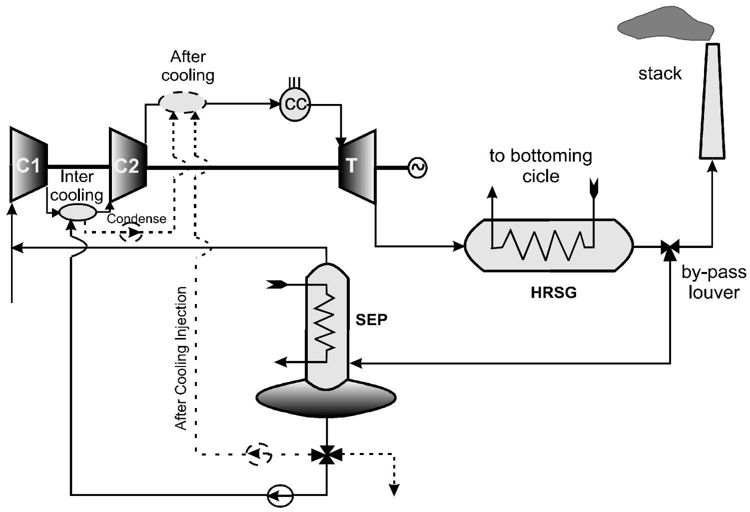

Figure 1. SCGT/CC power plant with compressor intercooling and aftercooling.

in excess of 60%, implies the loss of about 6 percentage points in efficiency. This is reflected by additional costs over the final unit cost of electricity ranging from 30 to 70% of the value without CO_2 sequestration (inclusive of the increase in capital cost of the power plant). However, the effective situation can be worse, because the CO_2 produced by plants based on open-cycle gas turbine technology is released in the exhaust gas at a concentration between 4 and 6%, that is, at a partial pressure much lower than the atmospheric value. This not only increases the work for its separation, but has a severe impact over the cost of the equipment needed for the separation itself, which must be sized according to the overall flowrate of exhaust gases which is very large as compared to the net CO_2 flowrate.

These considerations have fostered the research into power cycles allowing a substantial increase in the partial pressure of CO_2, or in alternative to its production in pressurised or even liquefied conditions. Some solutions of these types are described in the following.

3. The SCGT Concept

Cycle schemes developed around Semi-Closed Gas Turbines (SCGT) are the solution most close to present, open-cycle gas turbine technology (Facchini et al., 1996 a and b; Fiaschi and Manfrida, 1997; Mathieu and Bolland, 1997; Corti et al., 1998). In practice, adaptation of an existing gas turbine to this scheme of operation involves a substantial redesign of the combustor, and the addition of low-temperature equipment quite common in power plants and in chemical industries (by-pass and recirculation louvers, humidity separator, flue gas scrubbing equipment). The drawbacks over turbomachinery are typically small, and interesting solutions – such as self-produced water injection or absorption cooling - can be devised for recovering operation conditions very close to the design point.

The basic idea of a SCGT power plant, coupled to a Combined Cycle (CC), is shown in *Figure 1.*

The calculated efficiency/specific power performance map of the SCGT/CC cycle with spray intercooling and possibly aftercooling is shown in *Figure 2*. The cycle simulation includes a well-tested model for blade cooling, and refers to current-technology gas turbines; the efficiency, typically between 50 and 54%, does not include the heat supply for regeneration of the chemical scrubbing solution; the water-injected solutions achieve lower efficiencies, however they produce a relevant increase in specific power and tend to recover operation of the compressor close to the design point (recirculation of the warm exhaust displaces the operating point to surge conditions, while water injection always reduces the stall margin).

By all schemes, the exhaust gases are cooled down to about 40°C before recirculation; this allows the recovery of a large part of the combustion-produced water, which can be thus reinjected in the cycle. Without water reinjection, the cycle rejects combustion-originated water to the environment, so that the well-known heat sink effect is exploited for performance improvement (from a thermodynamics point of view, it would be more correct to refer to the higher heating value of the fuel; however, it is common practice in Europe to evaluate power plants with reference to the Lower Heating Value, so that this convention is retained in *Figure 2* and throughout this paper). On the whole, the amount of exhaust gas recirculated can total 60%, considering typical operation of gas turbine with a consistent overall excess air; this leads to a concentration of CO_2 in the exhaust (considering natural gas as fuel) larger than 12%. With such levels of concentration, scrubbing by aqueous or organic-base mixtures of amines is a well-tested technology, applied both for LPG purification and also by refineries and power plants. The basic scheme of the scrubbing system is shown in *Figure 3* (Corti et al. 1998 b).

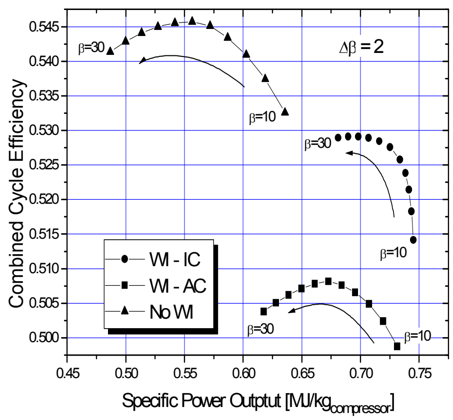

Figure 2. Performance map of the SCGY/CC cycle without and with reinjection of the recovered water (intercooled and aftercooled options).

By careful optimisation of the composition of the amines blend (including species as DEA and MDEA as well as the well-tested MEA), the heat required for regeneration of the scrubbing solution can be limited to less than 2.5 MJ/kg of CO_2 separated, at a removal efficiency level of 80% which is considered adequate in the light of containing the size and cost of the scrubbing system. Under these conditions, with a concentrated mixture of DEA in water (50%, requiring recently-developed corrosion inhibitors), the additional cost over the unit of electricity was estimated at about 4.2 \$cents/kWh (*Figure 4*), which corresponds to a percentage increment with respect to the base cost of electricity of about 70% (Corti et al., 1998a). To this, the additional cost for purification (99.5% purity), liquefaction, transport and storage of carbon dioxide separated from the flue gases was estimated at 0,54 \$cents/kWh referring to published data (Fujioka et al., 1997).

It is possible to apply the advantages of the SCGT solution also without the complication of a combined cycle, which implies referring to relatively large power plant sizes (larger than 150 Mwe). This can be obtained by the SCGT/RE configuration, shown in *Figure 5*.

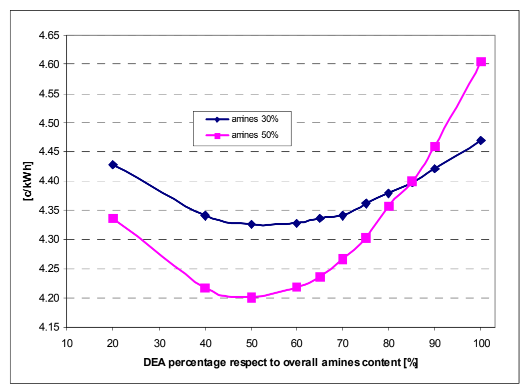

Figure 4. Additional cost (per unit energy of electricity) for CO_2 separation (SCGT system).

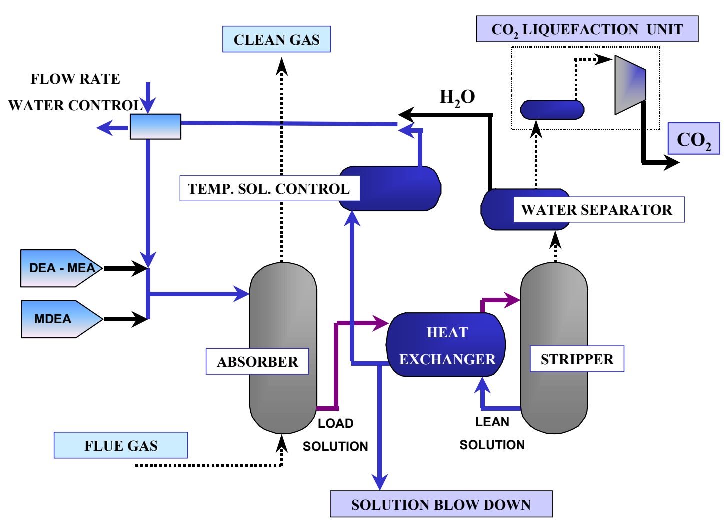

Figure 3. Schematic of the scrubbing system for CO_2 separation.

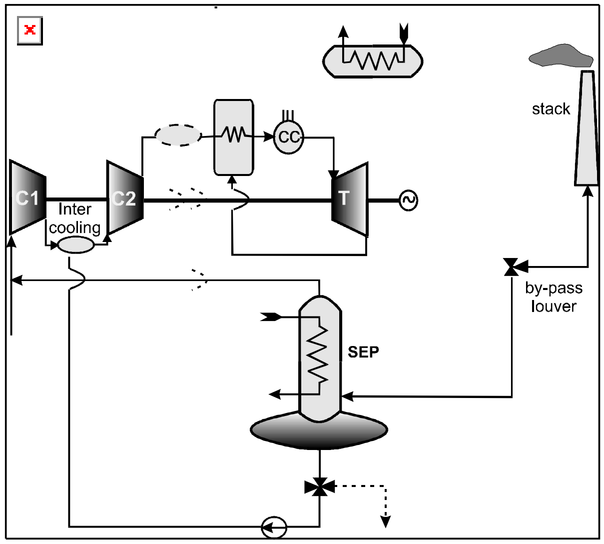

Figure 5. Schematic of the SCGT/RE cycle.

A peculiarity of the SCGT/RE cycle, developed around a regenerative-cycle gas turbine, is the recovery of low-temperature heat downstream of the regenerator , which is directly used to provide the heat supply at the scrubbing system. It should thus be considered that the efficiency levels shown in *Figure 6* are inclusive of the internal heat supply for the scrubbing system.

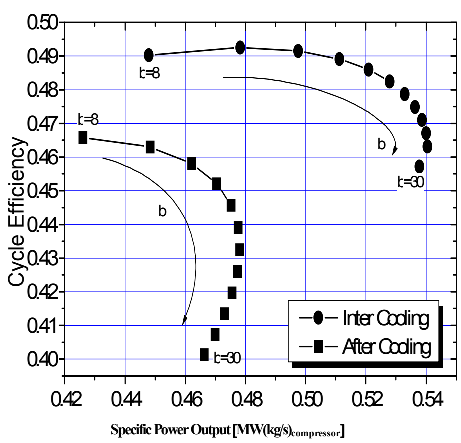

Figure 6. Performance of the SCGT/RE cycle.

The SCGT/RE solution is very attractive, as with a small penalty in efficiency in comparison to the SCGT/CC it has a much simpler layout and could be easily developed as a small-scale prototype.

All studies of SCGT power plants have been performed with a dedicated code, developed from a more general and well-tested version for open GT cycles; the simulation of the scrubbing system was performed by ASPEN+. The cycle study includes the estimate of exergy destructions, as is shown for the SCGT/RE case in *Figure 7*.

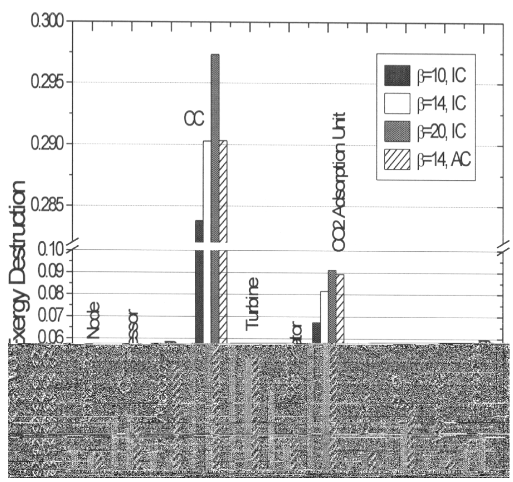

Figure 7. Exergy destructions in the SCGT/RE cycle.

Hybrid solutions between RE and CC schemes have also been studied (Fiaschi and Manfrida, 1998), which can offer advantages from the point of view of economy of heat transfer surfaces and off-design operation, with power modulation controlled by the degree of water injection. Preliminary studies of the size of the heat transfer equipment have also been performed (*Figure 8*), showing that the requirements are not beyond current compact heat exchanger technology.

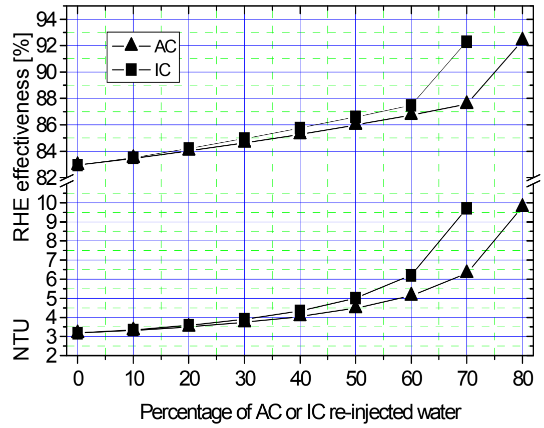

Figure 8. NTU and effectiveness of the regenerative heat exchanger. Sensitivity to level and mode of water injection. Hybrid CC/RE solution.

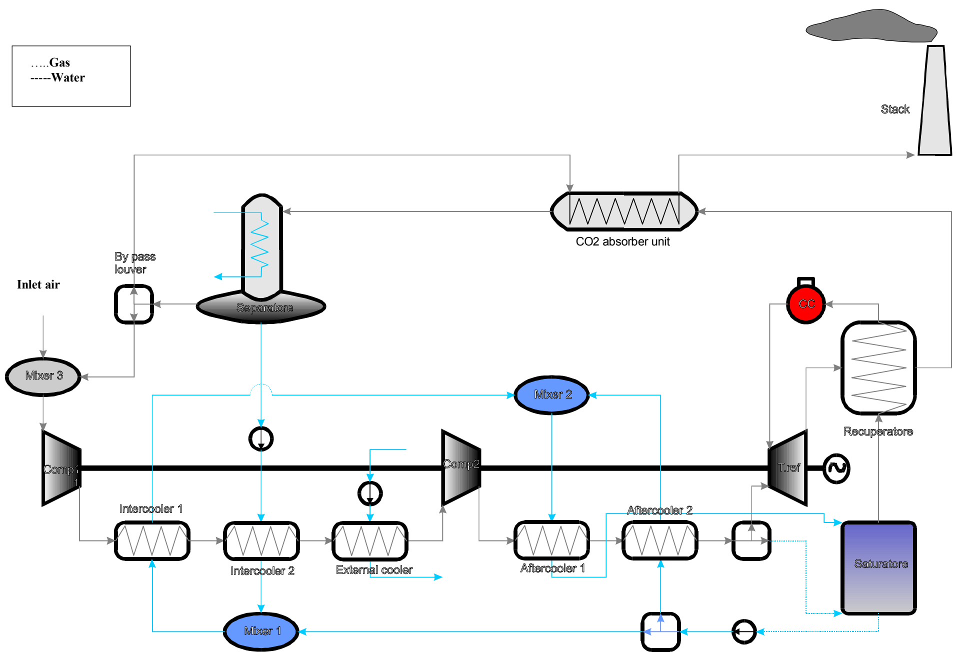

Figure 9. Schematic of the SC-HAT proposed power plant

The most recent developments in the SCGT concept address its combination with Humid Air Turbine (HAT) technology (Rao and Joiner, 1990; Day and Rao, 1993; Stecco et al., 1993 a and b; Xiao et al., 1994; Gallo et al., 1995).

HAT is a very attractive power cycle, undergoing prototype-level field testing on a small-scale pilot plant at University of Lund. The attractive features of the HAT cycle are its adaptability to small-size power plants, with outstanding performance levels within this category both for efficiency (in the range of 50%) and specific power (exceeding 600 kJ/kg). The drawbacks of HAT cycles and its derivatives (such as CHAT, a concept originally developed by Westinghouse) are a relatively complex cycle layout, with many regenerative heat and mass transfer components, and the open-cycle consumption of treated water, which implies a non-negligible running cost. The SC-HAT cycle takes advantage of the very low stack temperature obtainable by a HAT configuration, introducing water separation and recycling (as proposed by Desideri and Di Maria, 1997) and recirculation of about 40% of the turbine exhaust to compressor inlet. This leads again to a CO_2 concentration in the stack in the range of 15%, which allows an economic application of chemical scrubbing for CO_2

sequestration; the heat demand for regeneration of the scrubbing solution is completely provided within the cycle, after the RHE section (*Figure 9*).

With respect to the HAT cycle, recirculation of the exhaust and regenerative heat transfer to the scrubbing section imply a lower capability of water injection, which reaches typically 12% respective to dry compressor flowrate compared to the values around 20% achievable by HAT solutions. On the other hand, this 12% can be completely recovered by condensation of natural-gas-combustion water in the exhaust, so that the cycle becomes completely autonomous from the point of view of water consumption; moreover, the internal regenerative scheme can be simplified, with the elimination of the economiser for the injected water, leading to a simplified plant layout. The performance level of the SC-HAT can reach about 50% efficiency, inclusive of CO_2 sequestration, with a power output in the range of 500 kJ/kg (*Figure 10*).

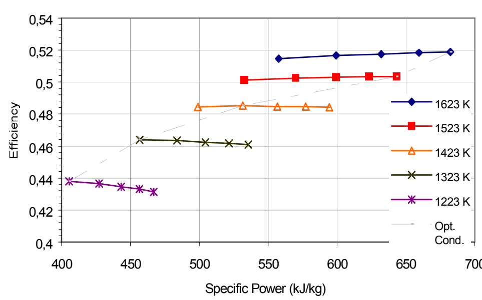

Figure 10. Expected performance of the basic SC- HAT cycle

Improvements to the SC-HAT are also possible with special reference to control of off-design and adaptability to current aeroderivative gas turbine engines (which are needed, as the optimising pressure ratio is relatively large). An interesting possibility is the addition of a simple absorption cooling section before recirculation of the exhaust. This is a technology which is currently being applied to a large advanced combined-cycle power plant using GE LM-6000 gas turbines, which are very sensitive to an eventual increase of compressor inlet temperature beyond ISO values. The experience over two years of operation of the system has demonstrated the capability of operating without problems over the whole year at temperatures lower than the 15°C ISO rated value, with substantial advantages in power output and large economic benefits. A similar system, with regenerative heat feeding from the exhaust between RHE and the heat transfer section to the scrubbing unit, can be added to the SC-HAT configuration. An absorption machine operating with a COP = 0,6 was assumed, fed by recovery of about 3% of the inlet heat. The addition of the absorption system allows a complete control of compressor inlet conditions(readjusted to the open-cycle ISO rating); the increase of CO_2 to about 4% leads to negligible effects, as it is coupled to a reduction of the water vapour content to 0,8%, which should be compared with the 2% value without absorption cooling of the recirculated stream (*Figure 11*).

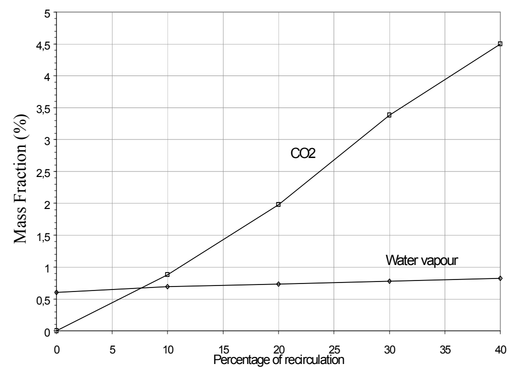

Figure 11. Adjustment of compressor inlet conditions by absorption cooling (SC-HAT)

Among the several SCGT power plant options investigated, the SCGT/RE appears to be the most attractive for a demonstration plant, even based on a small-size gas turbine; the SCGT/CC, with possible intercooling of the compressor, is a good candidate for the evolution of large, top-performance combined cycles (with power outputs exceeding 200 MWe); the SC-HAT solution appears to be the most convenient for mid-size levels (50-200 MWe).

The common limit of all SCGT options is that scrubbing of the exhaust gases takes place at atmospheric pressure, which implies a relatively large size and cost of the scrubbing system, which is proportional to the overall volume flowrate; moreover, the CO_2 is recovered at atmospheric pressure so that a further intercooled compression is needed before transport and final disposal. This has led to the study of more advanced schemes.

4. CO_2 Sequestration by IGCC Power Plants

A possible way to CO_2 sequestration and environmentally compatible use of fossil fuels is the separation of CO_2 under pressurised conditions within an integrated gas-sifier/combined cycle (IGCC) power plant. A few proposals in this direction can be found in the literature (Chiesa and Consonni, 1998; Pruschek et al., 1998); all these proposals consider physical absorption of CO_2 by means of solvents such as Selexol, Rectisol etc. When these solutions are examined, it can be seen that the complexity of the already complicated power plant is notably increased, and also that often the regeneration of the physical solvent calls for a heat demand exceeding 4 MJ/kgCO_2, together with a non-negligible compression work which is only partly counterbalanced by the recovery of expansion work in a set of small CO_2 turbines.

Based on the experience gained in fuel processing by chemical refineries, where amine scrubbing for gas purification is a well-known practice (Kohl and Riesenfeld, 1985; Cussler, 1997), a solution close to current IGCC technology, which uses pressurised cold gas purification with regenerative heat transfer to recover the sensible heat of the syngas, is proposed (*Figure 12*).

The conventional cold section of purification usually includes already an amine scrubbing section for H_2S removal; after this, a catalyzer for shift conversion of CO to CO_2 is added; after this, the CO_2 can be separated - still in pressurised conditions, with notable economy in the size of the whole scrubbing system - by further washing in a suitable amine solution. The syngas at gassifier exit is thus very rich in Hydrogen and can be used in the downstream combined-cycle section in a very environmentally-friendly way. The heat released in the catalytic CO to CO_2 converter is recovered within the combined cycle. Low-temperature heat for amine regeneration can be supplied by a steam extraction or by low-temperature heat recovery from the exhaust gas just before the stack. Another possibility, allowing interesting economies of heat transfer surface, is using low-temperature heat from the liquid quench of the gassifier. Simulation of this power plant, which is not very different from present large IGCC power plants installed in modern refineries, is being performed with an ASPEN+ model, and interesting results are expected in the near future.

5. Power Plants with Liquid CO_2 Sequestration (MATIANT-type)

Novel techniques which are very promising for the reduction of the environmental impact of energy conversion are being developed around cycle rejecting combustion products in liquid state (Mathieu et al., 1993, 1994 and 1995). These cycles offer very good overall performance combined with a fully integrated sequestration of CO_2 in liquid state, which enables an easy and effective sequestration.

The cycle here analysed, referred to as F-Matiant, is a simplified variant of the original Matiant cycle, with a single reheat in place of the double one. The plant layout is shown in *Figure 13*, and the cycle T-s diagram in Figure 14.

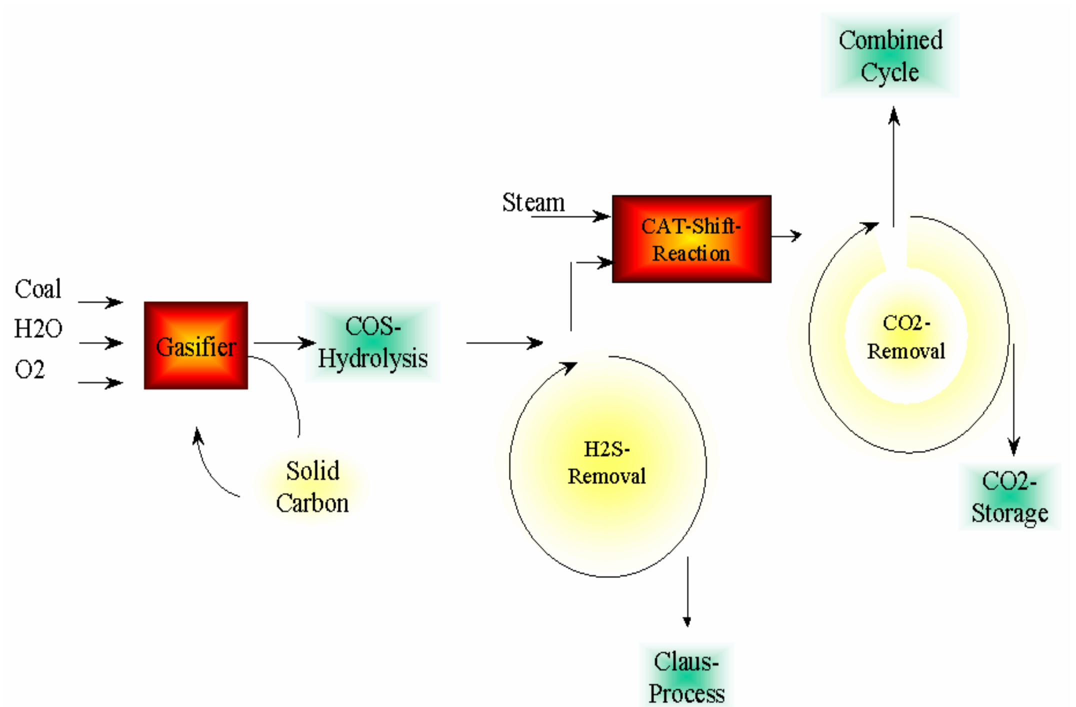

Figure 12. Basic layout of the gasifier section of an IGCC power plant, showing location for pressurised chemical scrubbing of CO_2

The simulation of the F-Matiant cycle was performed using an advanced thermodynamic simulator (EES by Klein and Alvarado, distributed by F-Chart software Ltd). The calculated performance is extremely attractive (*Figures 15* and *16*), with efficiency levels (inclusive of liquid CO_2 sequestration) approaching 50% at current technological levels, and exceeding well this value for expectable future developments. These efficiency figures are based on the lower-heating value of the fuel and do not consider the energy expenditure for production of the necessary O_2, which with current technologies entails the loss of about 6 percentage points in efficiency; the simulation does not include at present a model for cooled expansion in the high-temperature turbine, which according to Mathieu and Nihart (1998) should imply the loss of 2 to 3 percentage points in efficiency. The specific power of the F-Matiant cycle is also very large, typically from 750 to 1350 kJ/kg, indicating the possibility of developing the power plant around compact units, with easily predictable economic benefits. The drawbacks of this type of very advanced power cycle are the necessary development of dedicated turbomachinery components, such as the high-pressure, oxygen-blown combustion chamber, and the CO_2/H_2O turbine (which are not presently on the marketplace); and the necessary coupling to an oxygen separation plant. As for CO_2 compression and liquefaction, extensive expertise has been gained at industrial level for process plants, and only a size scaling is necessary (of the order of ten times the present size of compressors, for a reference power plant providing a power output of about 170 MWe). Further technical challenges are put by the heat exchanger design, with very large pressure difference on the two sides and difficult heat transfer conditions; and by the necessity of providing separation of impurities accumulating in the semi-closed loop.

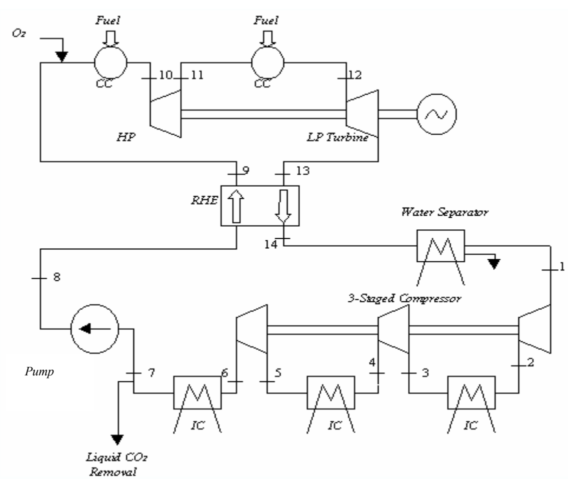

Figure 13. Layout of the semiclosed cycle with liquid sequestration of CO_2

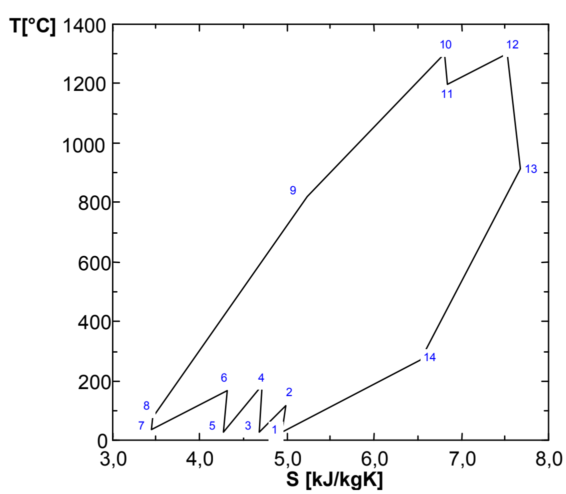

Figure 14. T-s diagram of the semiclosed cycle with liquid sequestration of CO_2

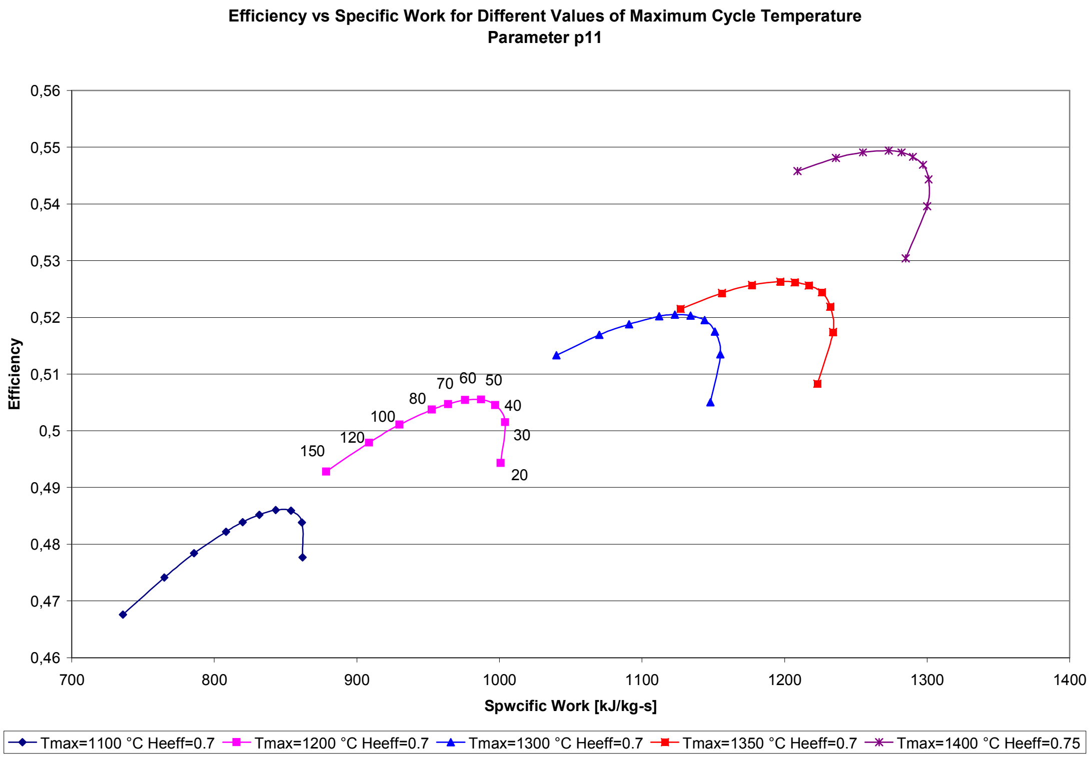

Figure 15. Performance map of F-Matiant cycle; sensitivity to max. firing temperature T_{10} and intermediate pressure p_{11}; $p_{max} = p_8 = 250$ bar; Heat exchanger effectiveness (HeEff) = 0,75

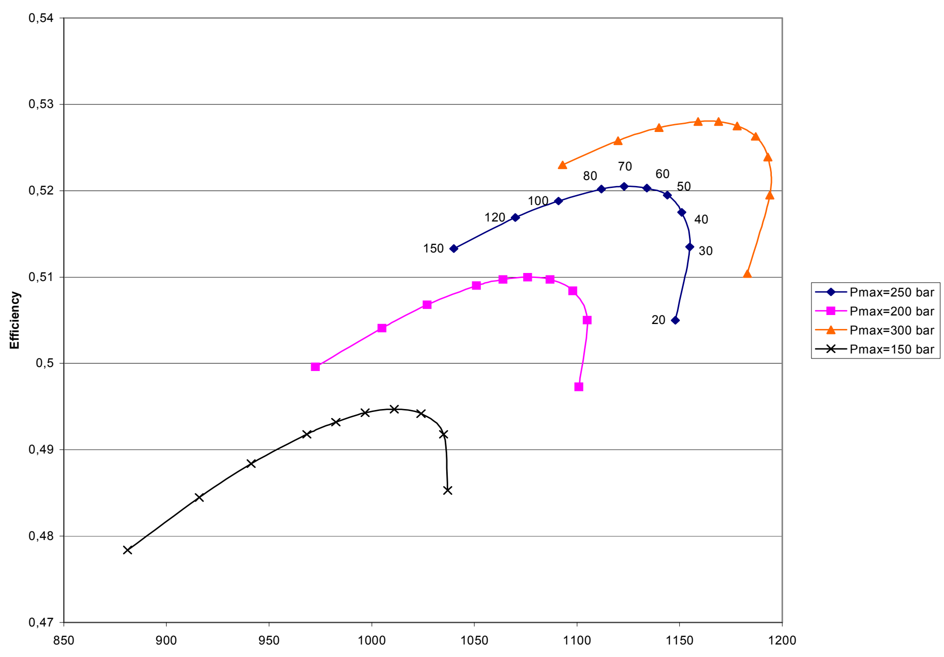

Figure 16. Performance map of F-Matiant cycle; sensitivity to max. cycle pressure $p_{max} = p_8$ and intermediate pressure p_{11}; firing temperature $T_{10} = 1400$ K, HeEff = 0,75.

Conclusions

CO_2 sequestration appears an innovative technology with some mature applications (e.g., separation by chemical scrubbing with amine solutions). Effective solutions to bridge the gap to carbon-sequestering power plants have been examined in this paper, and all of them have their relative merits and drawbacks.

Semiclosed gas-turbine based options, such as SCGT/CC, SCGT/RE, and finally SC-HAT, appear to have a potential for very easy development from existing GT engines, with minor modifications and the possibility of using water reinjection or absorption chilling of the recirculated stream to re-establish correct compressor inlet conditions.

Sequestration of CO_2 under pressurised conditions by IGCC power plants can also be a mature technology, with a smaller market potential and work to be done over industrial catalyst development.

Finally, cycles producing directly CO_2 in liquefied conditions are the most elegant solution for the energy-intensive use of fossil fuels; however, the development of these power plants demands the extensive development of dedicated equipment (turbomachines, combustion chamber, heat exchangers) which renders the application more difficult.

On the whole, all the presented solution offer relevant contributions to the reduction of the greenhouse effect and to the conservation of the environment.

Nomenclature

AC	After Cooling
CC	Combined Cycle
DEA	Diethyl-Ethyl-Amine
HAT	Humid Air Turbine
IC	Intermediate Cooling
HeEff	Effectiveness of the Regenerative Heat Exchanger
IGCC	Integrated Gassifier/Combined Cycle
MDEA	Methyl-Diethyl-Ethyl-Amine
MEA	Methyl-Ethyl-Amine
p	pressure
SCGT	Semi-Closed Gas Turbine
T	temperature
WI	Water Injection
β	Gas Turbine Pressure Ratio

References

Aspen Plus rel. 9.2-1 – User Guide – Volume 1 – 2.

Bidini, G., Desideri, U., Di Maria, F., 1996, “Thermodynamic Analysis of Injected Water Recovery Systems for the HAT Cycle”, *Proceedings, 1996 ASME Winter Annual Meeting*, Atlanta.

Chiesa P., Consonni S., 1998, “Shift reactors and physical absorption for low-CO_2 emission IGCCs”, 1996 IGTI Gas Turbine Conference and Exhibition, Stockholm, 1998.

Corti A., Fiaschi D., Manfrida G., 1998 a, "A Thermo-Economic Evaluation of the SCGT Cycle", Powergen Europe Conference and Exhibition, Milano, 1998.

Corti, A., Lombardi, L., Manfrida, G., 1998 b, “Absorption of CO_2 with amines in a semiclosed GT cycle: Plant Performance and Operating Costs”, ASME IGTI Gas Turbine Conference and Exhibition, Stockholm.

Corti, A., Failli, L., Fiaschi, D., Manfrida, G., 1998c , “Exergy analysis of two second-generation SCGT plant proposals”, ASME IGTI Gas Turbine Conference and Exhibition, Stockholm.

Cussler, E. L., 1997, "Diffusion", Cambridge University Press.

Day, W.H., and Rao, A.D., 1993, “FT4000 HAT with Natural Gas Fuel”, *Turbomachinery International*, Jan/Feb, pp. 22-29.

Desideri, U., and Di Maria, F., 1997, “Water Recovery from the HAT cycle exhaust gas: A possible solution to reduce stack temperature problems”, *International Journal of Energy Research*, Vol. 21, pp. 809-822.

DOE (Department of Energy), " Working paper on carbon sequestration science and technology", 1999.

Eliasson B., 1998, “The Power Industry and the CO_2 issue” Workshop on Zero Emission Power Plants, University of Liege, Belgium, 1998.

Facchini B., Fiaschi D., Manfrida G., 1996a “Semi-Closed Gas Turbine / Combined Cycle with Water Recovery”, 1996 IGTI Gas Turbine Conference and Exhibition.

Facchini B., Fiaschi D., Manfrida G., 1996b, "SCGT/CC: An Innovative Cycle with Advanced Environmental and Peakload Shaving Features", ECOS 96 Conference, Stockholm, 1996.

Fiaschi, D., Manfrida, G., 1997, “Exergy Analysis of the Semi-Closed Gas Turbine/Combined Cycle (SCGT/CC)”, FLOWERS ’97, Firenze.

Fiaschi, D., Manfrida, G., 1998, “A new semi-closed gas turbine cycle with CO_2 separation”, ECOS’98 Conference, Nancy, France.

Fujioka, Y., Ozaki, M., Takeuchi, K., Shindo, Y.;Herzog;H.J. (1997); ”Cost comparison in various CO_2 ocean disposal options"; Energy Convers. Mgmt, Vol.38, 1997.

Gallo, W.L.R., Bidini, G., Bettagli, N., Facchini, B., 1995, "The Evaporator Process Simulation and the HAT Cycle (Humid Air Turbine) Performance", *ASME Paper 95-CTP-59*.

Kohl A.L., Riesenfeld F.C., 1985, *Gas Depuration*, Gulf Publishing Company – Book Division.

Kongsjorden H., 1998, "Statoil CO_2 Program", Workshop on Zero Emission Power Plants, University of Liege, Belgium, 1998.

Langeland K., Wilhelmsen K., 1993, "A Study of the Costs and Energy Requirement for Carbon Dioxide Disposal", Energy Conversion and Management.

Lindgren, G., Eriksson, J., Bredhe, K. and Annerwall, K., 1992, "The HAT cycle, a possible future for power and cogeneration", in *Energy For The Transition Age*, S.S. Stecco and M.J. Moran, ed., Nova Science, New York, pp. 125-141.

Mathieu, P., De Rujck, J., 1993 "CO_2 Capture in CC and IGCC Power Plants Using a CO_2 Gas Turbine", Proceedings of IGTI Cogen-Turbo Congress, pp. 77-84, Bournemouth, UK.

Mathieu, Ph., Dechamps, P., Distelmans, M., 1994, "Concepts and Applications of CO_2 Gas Turbines", Power-Gen Europe '94, Cologne.

Mathieu, Ph., Chefneux, E., Dechamps, P., 1995, "Energy and Exergy Analysis of CO_2 based Combined Cycle Plants", "Second Law Analysis of Energy Systems: Towards the 21st century", Roma.

Matieu, Ph., Bolland., O., 1997, "Comparison of two CO_2 removal options in combined cycle power plants", FLOWERS '97, Firenze.

Mathieu, Ph., Nihart, R., 1998, "Sensitivity analysis of the Matiant cycle", ECOS'98 Conference, Nancy, France.

Pruschek R., Göttlicher G., 1996, "Comparison of CO_2 Removal Systems for fossil fuelled power plant processes" Proceedings of the III Int.Conf. on Carbon Dioxide Removal, Cambridge, MA, USA, 1996.

Pruschek R., Göttlicher G., Oelijeklaus, G., Haupt, G., Zimmermann, G., 1998, "Best Option for CO_2 Reduction in Fossil-Fired Power Stations", PowerGen 1998, Milan.

Rao, D., and Joiner, J.R., 1990, "A technical and economic evaluation of the humid air turbine cycle", *Proceedings, Electric Power Research Institute Contractors Meeting*, Palo Alto, California.

Stecco, S.S., Desideri, U., Facchini, B., and Bettagli, N., 1993a, "The humid air cycle: some thermodynamic consideration", *ASME Paper 93-GT-77*.

Stecco, S.S., Desideri, U., and Bettagli, N., 1993b, "Humid air gas turbine cycle. a possible optimization", *ASME Paper 93-GT-178*.

Xiao, Y., Lin, R., Cai,. R., 1994, "System Optimization of Humid Air Turbine Cycle", *ASME Paper 94-GT-240*