CO_2-free hydrogen production in a coal gasification pilot plant

A. Pettinau, F. Ferrara, C. Amorino
SOTACARBO S.p.A., c/o Grande Miniera di Serbariu,
09013, Carbonia, ITALY,
apettinau@sotacarbo.it

ABSTRACT

Coal gasification represents one of the most promising technology for large, medium and small scale hydrogen production for distributed power generation. Currently, the application of "zero emissions" hydrogen production and power generation technologies involves very high capital and operative costs. This need a great scientific and technical effort in order to optimize processes and equipments, thus reducing hydrogen production cost.
In this field, Sotacarbo is tuning technologies for the development of integrated processes for the combined production of hydrogen and electrical energy through coal gasification, with CO_2 capture. The process has been tested in a pilot platform, located in the Sotacarbo Research Centre in Carbonia (South-West Sardinia, Italy). The platform includes a 5 MW_{th} demonstrative plant and a fully equipped 200 kW_{th} pilot plant, both based on a fixed-bed, up-draft and air-blown gasification process.
This paper reports an analysis of the main results obtained in the first experimental campaigns on the platform, with particular reference to coal gasification and to the global carbon balance.
The experimental tests have been carried out with different operating conditions. In particular, a series of experimental tests have been developed in order to evaluate the possibility to substitute air with a mixture of oxygen and carbon dioxide as gasification agent, in order to increase CO_2 partial pressure in the carbon capture section, rising its performance.

Keywords: coal-to-hydrogen, carbon capture, CO_2-free, experimental plant.

1. INTRODUCTION

Worldwide, fossil fuels impact for more than 80% of the total primary energy supply (about 12 billions of tons of oil equivalent) and for 67% of the whole power generation (about 19 millions of GWh) [1]; their use involves the emission of greenhouse gas and, in particular, CO_2, which is the main responsible of global warming and climate change.
The possible options for mitigating greenhouse gas emissions include the reduction of energy consumption, a wider use of renewable and nuclear energy and the use of high efficiency fossil fuels-based power generation plants, equipped, when it is feasible, with a carbon capture and storage (CCS) system [2]. The introduction of a CCS system in a power generation plant fed with fossil fuels, involves a significant raise of capital and operating costs, but, in many cases, a series of economical advantages related with the introduction of the Emissions Trading System (ETS).
Coal gasification represents one of the most promising technologies for the application of pre-combustion carbon capture and storage systems to power generation plants fed with fossil fuels and, in particular, with coal.
This scenario justify the increasing interest to "near zero emissions" plants which allow hydrogen production from coal through gasification processes.
Currently, coal gasification, due to the low flexibility of synthesis gas (syngas) production,

are mainly used in large-scale IGCC (integrated gasification combined cycle) power plants in order to supply base energy load. But in a short-term future, the possibility to use syngas to co-produce hydrogen and electrical energy [3-5] could make gasification technologies very interesting even for medium and small-scale industrial applications.
Moreover, being coal price relatively stable [6], coal gasification technologies allow a competitive and secure production of hydrogen, one of the most promising energy carrier in a mid-term future [7-8]; as a matter of fact, it can be used as transport fuel or for distributed power generation through micro gas turbines or fuel cells [9-10].
As to this possibility, Sotacarbo, through different research projects regarding hydrogen production mainly for distributed power generation, is studying several integrated gasification and syngas treatment process configurations for a CO_2-free combined production of hydrogen and electrical energy, to be used in medium and small-scale commercial plants [11]. To this goal, a flexible and fully equipped pilot platform has been recently built up in the Sotacarbo Research Centre in Carbonia (South-West Sardinia, Italy). The platform includes a demonstrative (700 kg/h) and a pilot (35 kg/h) coal gasifier; in particular, the latter is equipped with a syngas treatment process for hydrogen and electrical energy production.
This paper reports a synthesis of the main experimental results obtained in the pilot plant in its "standard" operation, with particular reference to hydrogen production and CO_2 capture. Moreover, a series of experimental tests has been recently carried out (in close cooperation with ENEA, the Italian National Agency for Energy and Environment) in order to evaluate the possibility to feed the gasifier with a mixture of oxygen and carbon dioxide as gasification agent.

2. EXPERIMENTAL PLANT CONFIGURATION

In order to test different plant solutions and different operating conditions, a very flexible and simple layout for the pilot platform has been considered.
Currently, the Sotacarbo experimental equipment includes a demonstrative plant, based on a 5 MW_{th} (corresponding to 700 kg/h of coal) gasifier, and a pilot plant, which includes a 200 kW_{th} (35 kg/h) gasifier. Both these reactors are air-blown and fixed-bed, based on the up-draft Wellman-Galusha technology. The choice of this kind of gasification process is a consequence of a particular commercial interest in the field of medium and small scale industrial applications.
Pilot unit (figures 1 and 2), in which the experimental tests here reported have been carried out, has been developed in order to define an integrated syngas treatment process for a combined production of hydrogen and electrical energy. Raw syngas from the gasification process is sent to a skid which includes a wet scrubber (which reduces syngas temperature from about 300 °C to 50 °C and operates a primary dust and tar separation), a first cold gas desulphurization stage (which currently uses sodium hydroxide as solvent) and an electrostatic precipitator (ESP), which allows to achieve a fine particulate and tar removal. Downstream the ESP, syngas is split in two different streams: the main flow, about 80% of the produced syngas, is sent to the power generation line, whereas the secondary flow, that is the remaining 20%, is sent to the hydrogen production line [11].


Figure 1. The Sotacarbo pilot plant.

In particular, power generation line is constituted by

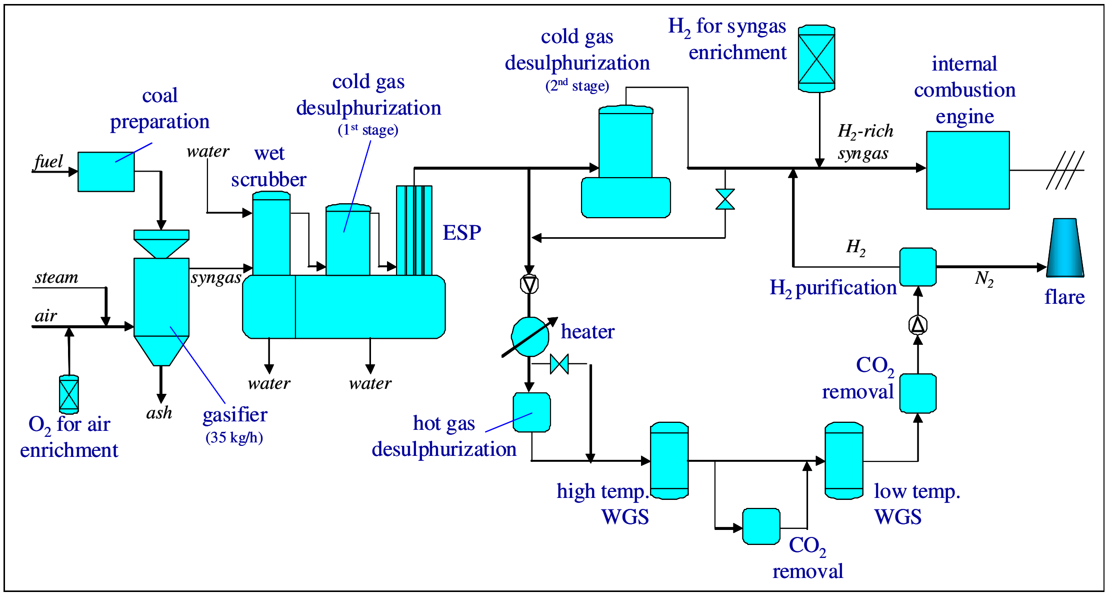

Figure 2. Pilot plant simplified scheme.

the second cold gas desulphurization stage (based on a hydrogen sulphide absorption with a mixture of sodium hydroxide and hypochlorite, diluted in water, as solvent), directly followed by a syngas-feed internal combustion engine.

On the other hand, hydrogen production line includes a compressor, which increases the pressure to about 0.14 MPa (in order to win the pressure drops of the treatment line), followed by an electric heater, a two-stages dry hot gas desulphurization process (which employs zinc oxide-based sorbents), an integrated CO-shift and CO_2 absorption system and a hydrogen purification system, based on the PSA (pressure swing adsorption) technology, which is widely common in the industrial applications due to its low costs [12-13]. A more detailed description of the combined CO-shift and CO_2 absorption section has been reported in an other paper [14], together with the main results of the preliminary tests on carbon dioxide separator. The size of the secondary syngas treatment line, even if much smaller than the size of commercial scale plants, should give reliable experimental data for the scale-up of future plants [15].

With the goal to ensure a full plant flexibility, as well as to simplify the management of the experimental pilot plant, the different cooling and heating devices are not fully integrated.

In order to test coal gasification process using a mixture of oxygen and carbon dioxide (together with steam) as gasification agent, pilot plant is equipped with a system (figure 3) which creates the feeding mixture with a fixed composition, taking O_2 and CO_2 directly from bottles (conceptually, in a hypothetical industrial application of this technology, carbon dioxide can be recirculated from CO_2 capture plant).

Figure 3. Oxygen and carbon dioxide mixer.

Finally, to support the experimental

tests, the plant is equipped with a sampling system which allows the monitoring of the process performances, with particular reference to syngas composition. In particular, for syngas analysis, upstream and downstream each plant component, a sampling outlet has been located in order to operate syngas analysis through a micro gas chromatograph and to evaluate the concentration of the main chemical compounds (CO_2, H_2, O_2, CO, CH_4, N_2, H_2S, COS, C_2H_6, C_3H_8) in the selected stream [11].

Figure 4. Pilot gasifier.

3. AIR-BLOWN GASIFICATION PERFORMANCE

During the first phase of the experimental tests, pilot gasifier (figure 4) has been tested for about 250 hours, between June 2008 and March 2009, with a low sulphur South African coal and a high sulphur Sardinian coal (from the Sulcis coal basin, in South West Sardinia), which ultimate analysis are shown in table 1. With reference to these feeding conditions, table 2 synthesizes the main performance of the "standard" (air-blown) gasification process.
In particular, the results shown in table 2 have been averaged during a two hours steady-state operation of the reactor and they have been assumed as "standard" operating conditions.
For both gasification feedstock, a syngas flow of about 100-130 Nm^3/h has been obtained, with a lower heating value of about 7.3-7.5 MJ/kg.
The gasifier yield (defined as the ratio between the volume flow of produced syngas, expressed in Nm^3/h, and the mass flow of primary fuel, in kg/h) is significantly higher for low sulphur coal, mainly due to the higher steam consumption.
Cold gas efficiency (calculated as a ratio between the chemical power associated with raw syngas and those associated with coal) significantly changes between the two conditions, mainly due to the different operating parameters and to the percentage of carbon which remains unreacted (typically between 2 and 5%, as results from the experimental tests).
Moreover, H_2S and COS concentration in raw syngas is strongly influenced by the sulphur content in primary fuel. In any case,

	South African coal	Sulcis coal
Carbon	68.54	53.17
Hydrogen	3.71	3.89
Nitrogen	1.50	1.29
Sulphur	0.55	5.98
Oxygen	5.35	6.75
Chlorine	0.05	0.10
Moisture	8.00	11.51
Ash	15.00	17.31
LHV (MJ/kg)	24.79	20.83

Table 1. South African and Sulcis coal ultimate analysis.

	South African coal	Sulcis coal
Operating parameters		
Coal feed (kg/h)	35.00	35.00
Air flow (kg/h)	49.00	44.35
Steam flow (kg/h)	36.00	21.00
Air/coal mass ratio	1.40	1.27
Steam/coal mass ratio	1.03	0.60
Dry syngas composition (molar fraction)		
CO	0.2241	0.1816
CO_2	0.1120	0.1316
H_2	0.3721	0.3663
N_2	0.2675	0.2823
CH_4	0.0201	0.0210
H_2S	0.0010	0.0126
COS	0.0001	0.0013
Ar	0.0031	0.0033
Gasifier performance		
Syngas flow (kg/h)	112.88	92.59
Syngas flow (Nm^3/h)	128.57	102.04
Syngas LHV (MJ/kg)	7.50	7.27
Syngas outlet temp. (°C)	300	270
Maximum temp. (°C)	875	850
Cold gas efficiency	97.57%	92.33%
Gasifier yield (Nm^3/kg)	3.67	2.91

Table 2. "Standard" air-blown gasification conditions [11].

the experimental tests shown that a little amount of this sulphur (in particular for Sulcis coal) is detained by the bottom ash.

Finally, an increasing of the air/coal mass ratio involves a reduction of hydrogen and carbon monoxide concentrations, due to the combination of two different phenomena: the rising temperature into the reactor, which reduces the effects of CO-shift conversion, and the rising nitrogen content, which dilutes raw syngas. On the other hand, steam injection promotes both the gasification and CO-shift reactions (increasing the reactants concentration and reducing the operating temperature into the reactor) and involves a rising of hydrogen concentration and a decreasing of CO content; carbon dioxide concentration remains about constant because the increasing of CO_2 content due to the CO-shift reaction is offset by the syngas dilution by steam [11].

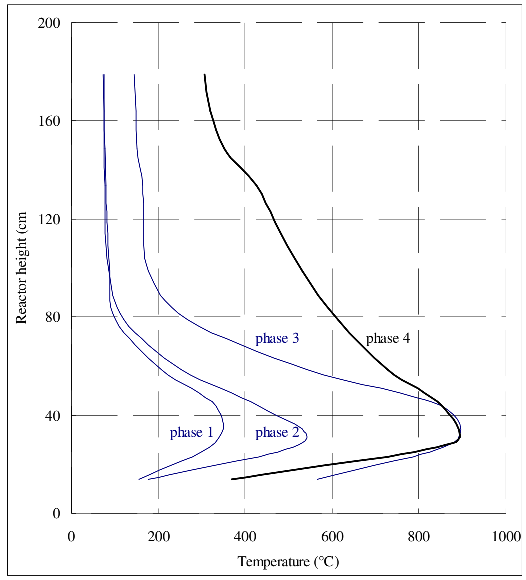

Fig. 5. Temperature profile during plant start-up [11].

Figure 5 shows the temperature profile into pilot gasifier, fed with low sulphur South African coal, measured with a series of 11 thermocouples located near the vertical axis. In particular, the three blue lines (curves 1, 2 and 3) correspond to three different phases of the gasifier start-up process, measured 20, 40 and 100 minutes later the start of the three ceramic lamps which heat the start-up fuel (wood pellets) before air injection, respectively. Phase 4 (black line) represents the steady-state condition (reached about 150 minutes later than phase 3). This curve allows to notice the different operating zones of the reactor [16-17]: the freeboard (at about 130 cm from the bottom of the reactor), the coal heating, drying, devolatilization and pyrolisis zone (60-130 cm), the combustion and gasification zone (30-60 cm) and the ash cooling area.

4. GASIFICATION TEST WITH MIXTURES OF OXYGEN AND CO_2

Conceptually, the possibility to separate carbon dioxide from clean syngas and inject it into the gasifier could increase the performance of the whole plant, allowing a substitution of nitrogen with CO_2 into the gasifier (with a simplifying of the hydrogen separation system) and a raise of CO_2 partial pressure into the absorber.

As for the performance of the gasification process, CO_2 takes part in a series of combustion and gasification reactions; therefore, a significant variation of its concentration into the reactor strongly affects the whole process.

In the scientific literature, a series of studies (mainly based on experimental tests) reports the influence of CO_2 injection in catalytic fluidized-bed biomass gasifiers or pyrolisers [18-21] or in high pressure entrained flow coal gasifiers [22]. In these cases, a CO_2-rich syngas characterized by a low H_2/CO ratio has been obtained by laboratory-scale experimental tests.

The results of these studies suggested to assess the effect of CO_2 in an autothermal coal gasification process in fixed-bed low-pressure reactor, as the Sotacarbo pilot gasifier. To this goal, a series of preliminary experimental tests has been carried out (in a close collaboration with ENEA, the Italian National Agency for Energy and Environment) in order to investigate the process and to collect the data need for a more detailed experimental campaigns.

For a series of technical reasons, the preliminary experimental tests with mixture of oxygen and CO_2 have been carried out significantly far from the "standard" operating conditions, in particular as for coal feed, limited to 5 kg/h of low sulphur South African coal (this choice, allowed by the great flexibility of the gasifier, has been taken in order to simplify temperature control during the tests). In order to compare air-blown gasification and CO_2 gasification, every test has been constituted by two different phases: in the first phase, the steady-state has been maintained for about one hour with air and subsequently air has been substituted with the oxidant mixture. Table 3 shows the main operating parameters in both these phases; raw syngas compositions and the gasification performance here reported have been averaged during a 100-minutes steady-state.

	air-blown gasification	CO_2 gasification
Operating parameters		
Coal feed (kg/h)	5.00	5.00
Oxidant flow (kg/h)	9.00	13.00
Steam flow (kg/h)	7.00	7.00
Operating pressure (MPa)	0.14	0.14
Dry syngas composition (molar fraction)		
CO	0.1325	0.2688
CO_2	0.1273	0.6208
H_2	0.1603	0.1032
N_2	0.5676	0.0061
CH_4	0.0105	Not detected
O_2	0.0018	0.0011
Gasifier performances		
Syngas flow (kg/h)	20.25	24.25
Syngas flow (Nm^3/h)	17.62	15.41
Syngas LHV (MJ/kg)	3.32	2.86
Syngas outlet temp. (°C)	336	510
Maximum temp. (°C)	831	848
Cold gas efficiency	54.20%	55.98%
Gasifier yield (Nm^3/kg)	3.52	3.08

Table 3. Air-blown and CO_2 gasification conditions.

Due to the very low coal feed and to the differences from the "standard" conditions, hydrogen content in dry raw syngas (air-blown gasification) is very low, and the lower heating value is 3.32 MJ/kg, to be compared with 7.50 MJ/kg in the "standard" conditions.

Steam/coal mass ratio is higher than that used in the "standard" conditions (1.4 vs. 1.0) in order to control the process. This parameter has been maintained constant in both phases of every test, together with the maximum temperature in the gasification and combustion zone (about 840 °C).

Oxidant flow has been assumed equal to 9 kg/h in the first phase (air-blown), while in the second phase 13 kg/h of mixture of oxygen (20% in volume) and carbon dioxide have been sent to the gasifier. Mass flow and composition of oxidant agent during the second phase (CO_2 gasification) have been calculated in order to maintain about constant, during both phases, the oxygen contribution into the reactor.

The increasing injection of gasification agents involves the raise of raw syngas mass flow and, subsequently, a decreasing of its lower heating value from 3.3 to about 2.9 MJ/kg, due to its higher dilution. On the other hand, syngas volume flow decreases, due to the significant differences between the molecular weight of syngas in the two different conditions.

As for temperature profile, while the maximum temperature in the gasification and combustion zone has been maintained about constant (840 °C, as already mentioned), a significant temperature rising (from 336 to 510 °C) has been measured in the top of the reactor. This variation reduce the effect of CO-shift reaction into the reactor (already limited by the high CO_2 concentration).

Figure 6 shows the concentrations of the main chemical species (hydrogen, nitrogen and carbon monoxide and dioxide) into the gasifier during the experimental tests, with particular reference to the period in which air has been substituted with the mixture of O_2 and CO_2.

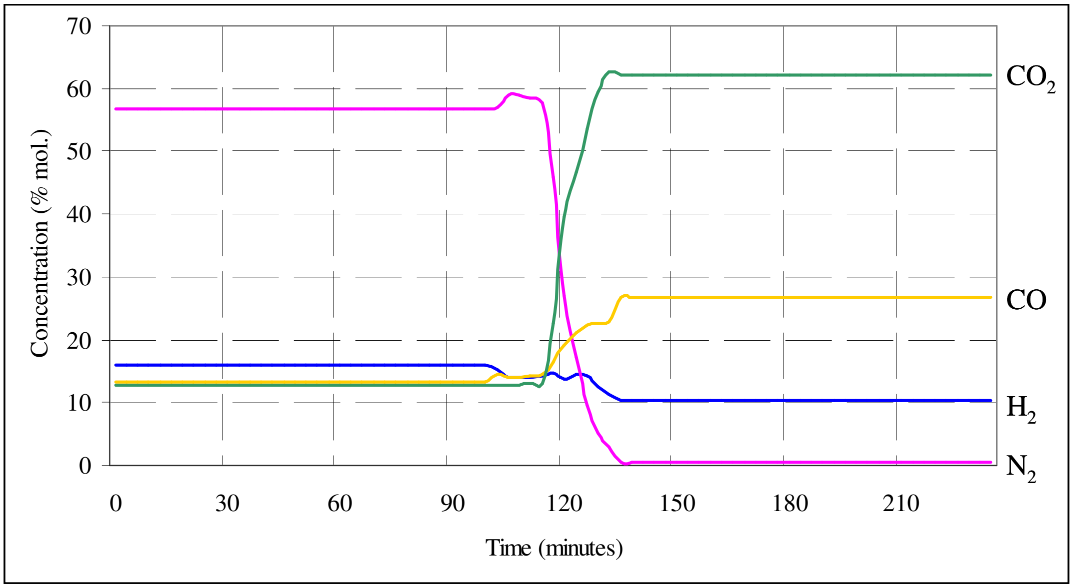

Figure 6. CO, CO_2, N_2 e H_2 concentrations.

After about 100 minutes of air-blown steady-state operation (the concentrations reported in figure 6 are averaged during this time-range), air has been instantly substituted with the mixture of O_2 and CO_2. As expected, nitrogen concentration quickly decreases (in 20 minutes reaches a value lower than 1%), while CO_2 concentration raises up to 62%. The process reaches a new steady-state condition about 35 minutes after the oxidant changing.

The introduction of a mixture of O_2 and CO_2 as oxidation agent involves a significant reduction of hydrogen concentrations (from 16 to 10%) and a raise of carbon monoxide content (from 13 to 27%). This is mainly due to the high CO_2 concentration, which shifts the equilibrium of the main gasification reactions and of the CO-shift conversion.

The effects of CO_2 gasification in syngas treatment line and, in particular, in the integrated CO-shift and CO_2 absorption section are currently under investigation.

5. GLOBAL PLANT BALANCE

A global mass balance of the Sotacarbo pilot plant, referred to the "standard" air-blown operating conditions, has been carried out in order to evaluate the global plant performance. The results here reported comes from a detailed analysis made up on the basis of the experimental data collected for every plant section. Through the elaboration of these data, a global mass balance of the plant has been developed and, for every section, performance and properties of each flow have been determined with good accuracy.

As for the gasification sections, the material balances show that hydrogen production is influenced by steam injection (71%), by hydrogen content in coal (28%, considering the primary fuel with its humidity) and, slightly, by air moisture (1%). Hydrogen content remains about constant through syngas cleaning processes (depulverization section and hot and cold gas desulphurization processes), while significantly changes through the CO-shift process. Globally, the gasification of 35 kg/h of low sulphur South African coal (considering that only 20% of produced syngas is sent to hydrogen production line) allows to produce 1.61 kg/h of hydrogen, characterized by a purity higher than 97% [23-24]. Hydrogen production slightly decreases (about 1.4 kg/h) when high sulphur Sulcis coal is gasified, due to the different operating conditions of the gasification process.

If all syngas should be sent to hydrogen production line, about 1.75 Nm^3 of hydrogen could be produced for every kilogram of low sulphur coal (about 1.38 Nm^3 through the gasification of high sulphur coal). In other words, for every kW of gasified coal, a production of about 0.75 kW of hydrogen has been obtained [23].

Considering the whole hydrogen production process, about 45% of hydrogen comes from the gasification steam, while 36% comes from steam injected into the CO-shift section, 18% comes from coal and only 1% comes from the gasification air.

As for pollutant emissions, wet scrubber allows a fine dust and tar removal, in particular for South African coal. When Sulcis coal is used, tar content in raw syngas is very high, and wet scrubber is not able to assure an adequate removal; even in this case, a fine tar removal can be achieved by using the electrostatic precipitator.

Both cold and hot gas desulphurization technologies allowed to obtain a final H_2S concentration lower than 10 ppm, compatible with the use of clean syngas to feed an internal combustion engine. In many cases, hot gas desulphurization system (based on zinc oxides as sorbent) allows to obtain an H_2S concentration lower than 1 ppm in the clean syngas, even with high sulphur Sulcis coal. These concentrations are compatible with some technologies for distributed power generation, like internal combustion engine, micro gas turbines and different kinds of fuel cell.

The preliminary experimental tests in the Sotacarbo pilot plant shows a great efficiency from carbon capture point of view. As a matter of facts, the plant includes two different CO_2 absorption reactors, operating with a removal efficiency of about 85% in their "standard" conditions.

Figure 7 shows the global carbon balance on the Sotacarbo pilot plant. A commercial "near zero emissions" configuration, equipped with a carbon capture and storage (CCS) system, should include the gasification section and the CO_2-free hydrogen production line. Therefore, the balance have been carried out, on the basis on the experimental data, with the hypothesis that all syngas from the depulverization system is heated, compressed and sent to the hot gas treatment line. For every stream, mass flow and lower heating value have been reported,

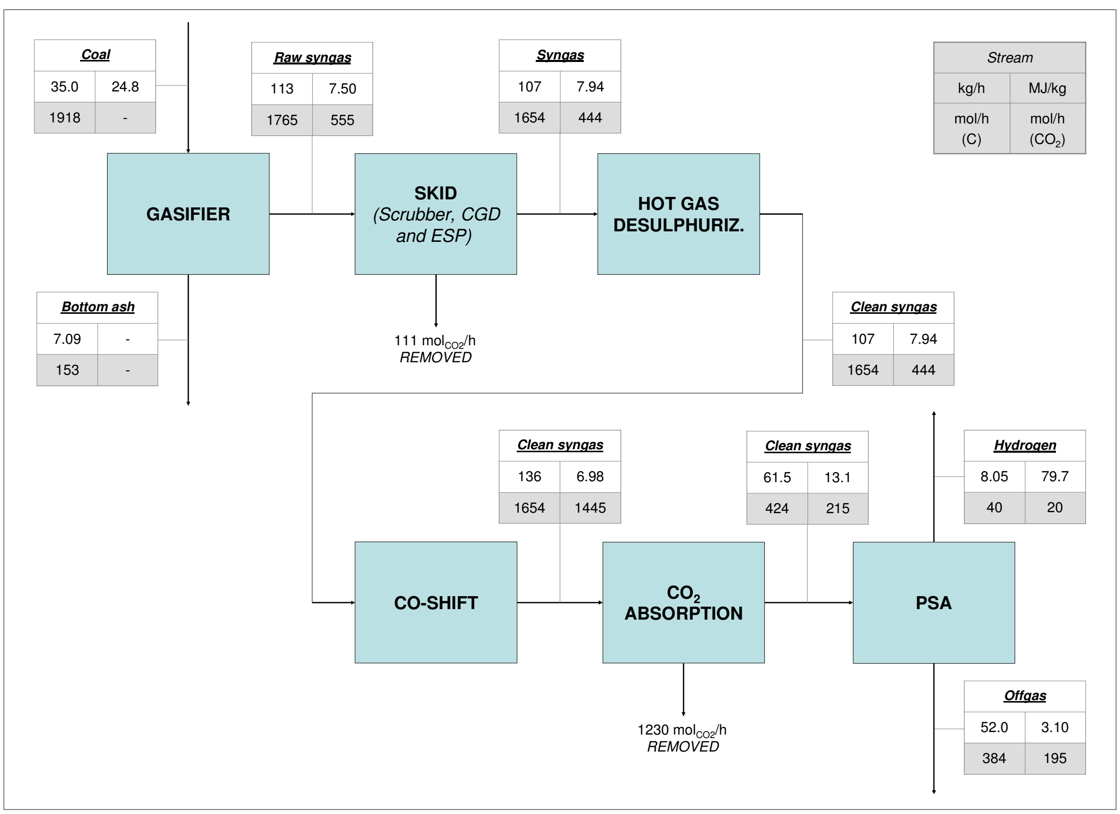

Figure 7. Global carbon balance.

together with molar flow of atomic carbon and of molecular CO_2. The reported data refer the air-blown gasification of 35 kg/h of low sulphur South African coal in "standard" conditions (see table 2).

Hypothetically, the combustion of 35 kg/h of South African coal (characterized by a carbon content of 68.54%, as shown in table 1) involves the production of 87.9 kg/h of CO_2. Through the gasification process, carbon reacts with gasification agents and is converted in a mixture of CO, CO_2, CH_4 and a little amount of COS, and a portion (typically 7-9% of total carbon amount in coal, as results from the experimental tests) remains unreacted in the bottom ash.

Carbon content in raw syngas remains about constant through wet scrubber and electrostatic precipitator (carbon amount removed as tar can be neglected), while a little variation take place into the first cold gas desulphurization stage. In particular, during the experimental tests with low sulphur coal, a pH of 9.5-10.0 has been assumed for the desulphurization solvent, with a subsequent absorption of about 20% of CO_2; on the other hand, when high sulphur Sulcis coal has been used, in order to reduce H_2S content in syngas a solvent solution characterized by a pH of 10.0-10.5 has been used, with a subsequent CO_2 removal efficiency higher than 80%.

Through the two-stage CO-shift section (in the reported analysis, the intermediate CO_2 removal system has not been used, in order to verify the performance of a single-stage carbon capture), carbon monoxide reacts with steam producing hydrogen and carbon dioxide, globally, syngas is enriched in hydrogen and CO_2 but, obviously, the global carbon content remains constant.

Carbon dioxide absorption through a 5 M solution of monoethanolamine operates with a global efficiency of about 85%. This process allows to separate 1230 moles per hour of carbon. The remaining carbon content in syngas is separated through PSA (pressure swing adsorption) and can be found in offgas, sent to the flare, except for about 40 mol/h, which remains in hydrogen-rich stream.

Globally, the gasification of 35 kg/h of South African coal, with the hypothesis that all syngas should be sent to the hydrogen production line, involves the emission of 17 kg of CO_2, with a global removal efficiency slightly higher than about 80%.

6. CONCLUSIONS

The experimental tests carried out in the Sotacarbo coal-to-hydrogen pilot plant allowed both to obtain some data and to evaluate the performances of each plant section. The conventional processes used for syngas treatment (wet scrubber, cold and hot gas desulphurization, CO-shift, CO_2 absorption and PSA), integrated in a non conventional configuration (the integration between the different equipments is the main goal of the experimentation), allow the production of a hydrogen stream with a purity of about 97%; even if this purity is relatively low with respect to the current state of the art in hydrogen purification processes, it is suitable for the use in an internal combustion engine. In any case, it is possible to obtain a very high purity hydrogen (up to 99.999%) by using a more sophisticated PSA process [12] when the technology will be scaled-up to an industrial application for distributed power generation.

During the experimental tests, a hydrogen flow about 1.3-1.6 kg/h (depending to the plant feed and to the operative condition) have been produced through the gasification of 35 kg/h of coal. The specific hydrogen production is higher for the gasification of low sulphur South African coal: 1.75 Nm^3 per kilogram of coal, to be compared with 1.38 Nm^3 obtained from high sulphur Sulcis coal. Obviously, in the Sotacarbo pilot plant, hydrogen production has not been optimized, due to the experimental aim of the plant. This justify the relatively high energy content in the offgas, which is currently sent to the flare; with a view to the

application of this technology to an industrial coal-to-hydrogen plant, it is possible to maximize hydrogen production (thus reducing energy content in the offgas) or to reduce hydrogen production and use the offgas for the co-production of electrical energy.
As for pollutant compounds, the integration between wet scrubber and electrostatic precipitator allows to obtain a negligible dust emission, while tar content is strongly reduced, even when Sulcis coal is gasified. Hot gas desulphurization process allows to obtain a final H_2S concentration lower than 10 ppm (even with high sulphur Sulcis coal) and, in many cases, lower than 1 ppm.
Global carbon dioxide emissions can be strongly reduced (up to 80%) through a one-stage CO_2 capture plant, which is characterized by an adsorption efficiency of about 85%. The global emission can be further reduced by using a two-stage capture system, with a first intermediate CO_2 absorption stage between high and low temperature CO-shift reactors. With reference to an industrial application of the technology, a two-stage CO_2 capture system equipped with a solvent regeneration section and a carbon sequestration plant should allow to separate and store more than 85-90% of the global carbon content, with some economical advantages related with the International Emissions Trading.
The studies and experimentations carried out on the Sotacarbo pilot platform represent only the first phase of a large series of experimental campaigns which has been planned in order to optimize gasification process and syngas treatment line. Some experimental tests will be carry out in order to evaluate the performance of the gasifier with air enrichment in oxygen. As a matter of fact, as results by a preliminary theoretical analysis [25], a rising of oxygen purity in the gasification agent involves a reduction of syngas dilution with nitrogen and, as a consequence, a decreasing of syngas flow, with a contemporary rising of its lower heating value. Moreover, the possibility to operate a co-gasification of coal with biomass or wastes [26] (for example pelletized municipal solid waste or refuse derived fuels) will be also investigated. Finally, as for syngas treatment line, the possibility to test different sorbents and catalysts (in particular for hot gas desulphurization and CO-shift process) will be soon investigated, together with the use of produced hydrogen to feed advanced power generation systems like fuel cell and micro gas turbines [9-10].

AKNOWLEDGEMENTS

The experimental tests of coal-gasification with mixtures of oxygen and carbon dioxide have been developed in the framework of Electric System Research program coordinated by ENEA (the Italian National Agency for Energy and Environment) and funded by the Italian Ministry of Economic Development.

REFERENCES

[1] International Energy Agency, www.iea.org, 2008.
[2] M. Genova, R. Casirati, A. Calabrò, P. Chiesa, D. Cocco, A. Pettinau. *PR.A.T.O.: a project to optimize pre-combustion technology for CO_2 capture*. Proc. Coal-Gen Europe 2008, Warsaw, Poland, July 1-3, 2008.
[3] E. Shoko, B. McLellan, A. L. Dicks, J. C. Diniz da Costa. *Hydrogen from coal: production and utilization technologies*. International Journal of Coal Geology 65 (2006) 213-222.
[4] A. Perna. *Combined power and hydrogen production from coal. Part A – Analysis of IGHP plants*. International Journal of Hydrogen Energy 33 (2008) 2957-2964.
[5] S. P. Cicconardi, A. Perna, G. Spazzafumo. *Combined power and hydrogen production from coal. Part B: Comparison between the IGHP and CPH systems*. International Journal of Hydrogen Energy 33 (2008) 4397-4404.

[6] U. S. Department of Energy. *Annual Energy Outlook 2008*. Available at www.eia.doe.gov.
[7] M. Balat. *Potential importance of hydrogen as a future solution to environmental and transportation problems*. International Journal of Hydrogen Energy 33 (2008) 4013-4029.
[8] C. C. Cormos, F. Starr, E. Tzimas, S. Peteves. *Innovative concepts for hydrogen production processes based on coal gasification with CO_2 capture*. International Journal of Hydrogen Energy 33 (2008) 1286-1294.
[9] P. Lisbona, L. M. Romeo. *Enhanced coal gasification heated by unmixed combustion with an hybrid system of SOFC/GT*. International Journal of Hydrogen Energy 33 (2008) 5755-5764.
[10] B. Fredriksson Möller, J. Arriagada, M. Assadi, I. Potts. *Optimisation of a SOFC/GT system with CO_2-capture*. Journal of Power Sources 131 (2004) 320-326.
[11] A. Pettinau, F. Ferrara, A. Orsini, G. Calì, M. Caboni, C. Amorino. *Experimental tests in the Sotacarbo laboratory scale coal-to-hydrogen plant*. Proc. 4th International Conference on Clean Coal Technologies, Dresden, Germany, May 18-21, 2009.
[12] P. Chiesa, S. Consonni, T. Kreutz, R. Williams. *Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part A: Performance and emissions*. International Journal of Hydrogen Energy 30 (2005) 747-767.
[13] T. Kreutz, R. Williams, S. Consonni, P. Chiesa. *Co-production of hydrogen, electricity and CO_2 from coal with commercially ready technology. Part B: Economic analysis*. International Journal of Hydrogen Energy 30 (2005) 769-784.
[14] F. Ferrara, G. Calì, C. Frau, A. Pettinau. *Experimental and numerical assessment of the CO_2 absorption process in the Sotacarbo pilot platform*. Proc. 1st International Conference on Sustainable Fossil Fuels for Future Energy, Rome, July 6-10, 2009.
[15] C. Amorino, A. Pettinau, F. Larceri. *The Sotacarbo coal gasification pilot plant for hydrogen production and CO_2 removal*. Proc. 24th International Pittsburgh Coal Conference, Johannesburg, South Africa, September 10-14, 2007.
[16] M. L. Hobbs, P. T. Radulovic, L. D. Smoot. *Modeling fixed-bed coal gasifier*. A.I.Ch.E. Journal 38 (1992) 681-702.
[17] O. H. Hahn, P. D. Wesley, B. A. Swisshelm, S. Maples, J. Withrow. *A mass and energy balance of a Wellman-Galusha gasifier*. Fuel Processing Technology 2 (1979) 332-334.
[18] L. Garcia, M. L. Salvador, J. Arauzo, R. Bilbao. *CO_2 as gasifying agent for gas production from pine sawdust at low temperatures using Ni/Al coprecipitated catalyst*. Fuel Processing Technology 69 (2001) 157-174.
[19] D. Wang, S. Czernik, D. Montané, M. Mann, E. Chornet. *Biomass to hydrogen via fast pyrolisis and catalytic steam reforming of the pyrolisis oil or its fraction*. Industrial Engineering Chemistry Research 36 (1997) 1507-1518.
[20] D. Wang, S. Czernik, E. Chornet. *Production of hydrogen from biomass by catalytic steam reforming of fast pyrolisis oils*. Energy & Fuels 12 (1998) 19-24.
[21] J. Arauzo, D. Radlein, J. Piskors, D. S. Scott. *A New Catalyst for the Catalytic Gasification of Biomass*. Energy & Fuels 8 (1994) 1192-1196.
[22] S. Kajitani, N. Suzuki, M. Ashizawa, S. Hara. *CO_2 gasification rate analysis of coal char in entrained flow coal gasifier*. Proc. 21st International Pittsburgh Coal Conference, Osaka, Japan, September 13-17, 2004.
[23] A. Pettinau, A. Orsini, G. Calì, F. Ferrara. *The Sotacarbo coal gasification experimental plant for a CO_2-free hydrogen production*. Proc. International Conference HYPOTHESIS VIII, Lisbon, Portugal, April 1-3, 2009.
[24] F. Ferrara, A. Orsini, G. Calì, A. Pettinau. *Coal gasification in the Sotacarbo coal-to-hydrogen experimental plant*. Proc. International Conference HYPOTHESIS VIII, Lisbon, Portugal, April 1-3, 2009.

[25] A. Pettinau, A. Orsini, C. Amorino, D. Cocco. *Sotacarbo R&D project for hydrohgen production from coal and CO_2 removal*. Proc. 22nd International Pittsburgh Coal Conference, Pittsburgh, USA, September 12-15, 2005.
[26] M. He, Z. Hu, B. Xiao, J. Li, X. Guo, S. Luo, F. Yang, Y. Feng, G. Yang, S. Liu. *Hydrogen-rich gas from catalytic steam gasification of municipal solid waste (MSW): Influence of catalyst and temperature on yield and product composition*. International Journal of Hydrogen Energy 34 (2009) 195-203.