

# Experimental tests in the Sotacarbo laboratory scale coal-to-hydrogen plant

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## 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 the hydrogen production cost.

In this field, Sotacarbo has build up a pilot platform for a combined production of hydrogen and electrical energy from coal. The platform includes two different units: a 5 MW<sub>t</sub> pilot plant (with a fuel capacity of 700 kg/h of coal) and a 200 kW<sub>t</sub> “laboratory scale” plant (feed with 35 kg/h of coal). In particular, the laboratory scale plant has been designed to develop and optimize the syngas treatment line for hydrogen production and power generation; therefore, the plant includes a fixed-bed up-draft gasifier, a syngas depulveration system, a cold and hot gas desulphurization processes, an integrated CO-shift and CO<sub>2</sub> absorption system, a PSA section for hydrogen purification and a syngas-feed internal combustion engine for power generation.

This paper reports a critical analysis of the main results obtained in the first experimental campaigns on the laboratory scale plant, with particular reference on coal gasification and hydrogen production.

**Keywords:** *coal gasification, coal-to-hydrogen, carbon capture, experimental plant*

## 1 Introduction

All over the world, the global hydrogen production is greater than one billion of cubic meters per day and currently it is mainly used in chemical and refining processes and as intermediate for the production of chemicals, such as methanol, ammonia, urea, methane or Fischer-Tropsch chemicals [1]. In addition to these conventional uses, hydrogen promises to become the most important energy carrier in a mid-term future [2-3]. As a matter of fact, hydrogen can be used as transport fuel or for distributed power generation through micro gas turbines or fuel cells [4-5], with significant advantages from the environmental point of view.

Nowadays, coal contributes for about 18% on the hydrogen production worldwide [1], while the remaining production comes from natural gas (48%), oil (30%) and water electrolysis (4%). But its relatively stable price [6] can represent an important advantages, from the economical point of view, with respect with oil and natural gas.

Hydrogen can be produced from coal through gasification technologies. In particular, gasification processes, 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 [7-9] could make gasification technologies very interesting even for medium and small-scale industrial applications.

As to this possibility, Sotacarbo, through different research projects regarding hydrogen production mainly for distributed power generation, is developing an integrated gasification and syngas treatment process for combined production of hydrogen and electrical energy, to be used in medium and small-scale commercial plants. To this goal, a flexible and fully equipped pilot platform has been recently built up at the Sotacarbo Research Centre in Carbonia, in South-West Sardinia (Italy). The platform includes a pilot (700 kg/h) and a laboratory scale (35 kg/h) coal gasifiers; in particular, the latter is equipped with a syngas treatment process for hydrogen and electrical energy production.

This paper reports the main experimental results obtained in the laboratory scale plant; in particular, the main performances of the gasification section and a global plant balance, mainly focused on hydrogen production, has been reported.

## 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 pilot plant, based on a 5 MW<sub>th</sub> (corresponding to 700 kg/h of coal) gasifier, and a laboratory scale plant, based on a 200 kW<sub>th</sub> (35 kg/h) gasifier. Both gasifiers are air-blown and fixed-bed reactors, 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.

Whereas the main goal of the experimental tests on the pilot plant is the optimization of the gasification process and the definition of start-up and shut-down procedures, the laboratory scale plant (figure 1) is used to develop the syngas treatment process for hydrogen production. Therefore, while the pilot plant is only equipped with a wet scrubber (for syngas cooling and tar and dust removal) and the cold syngas is directly sent to a flare, the laboratory scale plant is equipped with a complete and flexible syngas treatment process for hydrogen production [10].

In the Sotacarbo laboratory scale plant (schematically shown in figure 2), the raw syngas from the gasification process is sent to a skid which includes a wet scrubber (which reduce 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 a soda-based solvent) and an



Fig. 1. The Sotacarbo laboratory scale plant.

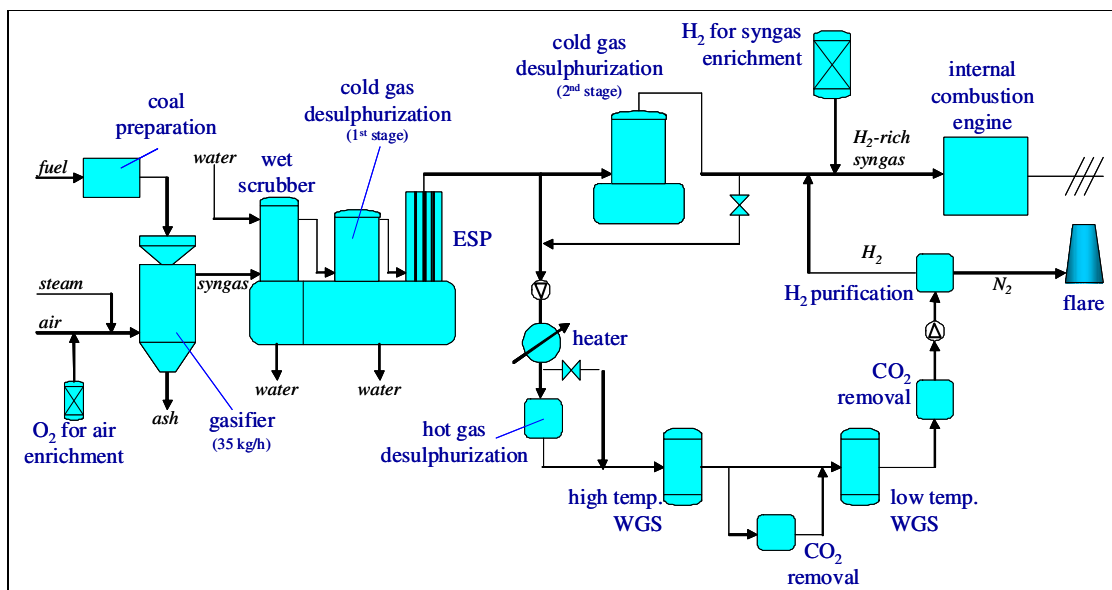


Fig. 2. Laboratory scale plant simplified scheme.

electrostatic precipitator (ESP), which allows to achieve a fine particulate and tar removal. According to the design conditions, downstream the ESP, the syngas is split into two streams: the main stream, about 80% of the produced syngas, is sent to the power generation line, whereas the secondary stream, that is the remaining 20% of the produced syngas, is sent to the hydrogen production line.

In particular, the power generation line is constituted by the second cold gas desulphurization stage (based on a hydrogen sulphide absorption with a mixture of soda and sodium hypochlorite, diluted in water, as solvent), directly followed by a syngas-fed internal combustion engine.

On the other hand, the hydrogen production line includes a compressor, which increases the pressure to about 1.4 bar (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<sub>2</sub> 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 [11-12]. 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 the future plants [10].

The laboratory scale gasifier is designed to operate with enriched air (simply by using an oxygen bottle) and to allow the co-gasification of coal, wastes and biomass (such as olive bagasse, refuse derived fuel and tyres). Moreover, the possibility to test the internal combustion engine with hydrogen enriched fuels has been considered. In this case, the hydrogen produced by the hot gas treatment line can be mixed with the clean syngas from the cold gas desulphurization process (second stage); otherwise, it is possible to operate the hydrogen enrichment simply by using a hydrogen bottle located upstream the engine.

In order 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. However, the aforementioned layout, if necessary, can be easily modified without significant costs.

In order 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 the syngas analysis, the plant is equipped with a system for the real-time measurement of oxygen concentration in raw syngas (this measure plays a double role of safety control, to avoid the formation of explosive atmosphere, and performance indicator for the gasification process). Moreover, upstream and downstream each plant component, has been situated a sampling outlet in order to operate the syngas analysis through a micro gas chromatograph and to evaluate the concentration of the main chemical compounds ( $\text{CO}_2$ ,  $\text{H}_2$ ,  $\text{O}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{N}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{COS}$ ,  $\text{C}_2\text{H}_6$ ,  $\text{C}_3\text{H}_8$ ) in the selected stream. Even if this system doesn't allow a real-time monitoring of syngas composition, it gives a detailed measure of the concentration of each chemical species every 3 minutes about, which represents a time range negligible with respect to the plant dynamics.

### 3 The Gasification performances

The laboratory scale gasifier is a fixed-bed up-draft Wellman-Galusha reactor, developed and manufactured by Ansaldo Ricerche S.p.A. [10], which is characterized by a very flexible fuel capacity, with a maximum of 35 kg/h of primary fuel.

In this first phase of the research, the laboratory scale gasifier has been tested for about 200 hours, between June and December 2008, with a low sulphur South African coal (LSC) and a high sulphur Sardinian coal (HSC, from the Sulcis coal basin, in South West Sardinia), which ultimate analysis are shown in table 1.

The main performance of the gasification process are synthesized in table 2, with reference to three different feeding conditions: low sulphur coal, high sulphur coal and a blend composed by both South African and Sulcis coal (each one with a percentage of 50% in terms of energy contribution). These results have been averaged during a two hours steady-state operation of the reactor and they have been assumed as "standard operating condition".

For the three gasification conditions, is it possible to notice a syngas flow of about 100-130  $\text{Nm}^3/\text{h}$ .

The cold gas efficiency has been calculated as a ratio between the chemical power associated with raw syngas and those associated with coal (the other power contributions such as those associated with air and steam injection are not considered in this parameter); therefore, the value of this efficiency is a direct consequence of coal lower heating value and syngas composition. The latter is strongly influenced by the gasification parameters, such as the temperature profile into the reactor, the air/coal and steam/coal

Table 1. Sulcis and South African coal ultimate analysis.

	LSC: S.A. coal	HSC: 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 2. Main results of the gasification tests.

	LSC	LSC + HSC	HSC
Input data			
Coal feed (kg/h)	35.00	35.00	35.00
Air flow (kg/h)	49.00	49.00	44.35
Steam flow (kg/h)	36.00	37.30	21.00
Air/coal mass ratio	1.40	1.40	1.27
Steam/coal mass ratio	1.03	1.07	0.60
Dry syngas composition (molar fraction)			
$\text{CO}$	0.2241	0.2162	0.1816
$\text{CO}_2$	0.1120	0.1103	0.1316
$\text{H}_2$	0.3721	0.3698	0.3663
$\text{N}_2$	0.2675	0.2815	0.2823
$\text{CH}_4$	0.0201	0.0121	0.0210
$\text{H}_2\text{S}$	0.0010	0.0064	0.0126
$\text{COS}$	0.0001	0.0004	0.0013
Ar	0.0031	0.0033	0.0033
Gasifier performances			
Syngas flow (kg/h)	112.88	113.86	92.59
Syngas flow ( $\text{Nm}^3/\text{h}$ )	128.57	129.38	102.04
Syngas LHV (MJ/kg)	7.50	6.65	7.27
Gas outlet temp. ( $^{\circ}\text{C}$ )	300	350	270
Maximum temp. ( $^{\circ}\text{C}$ )	875	890	850
Cold gas efficiency	97.57%	94.84%	92.33%
Gasifier yield ( $\text{Nm}^3/\text{kg}$ )	3.67	3.70	2.91

mass ratios and the percentage of carbon which remains unreacted (typically between 2 and 5%, as results from the experimental tests). This justifies the significant variation of the cold gas efficiency in the three considered cases.

The gasifier yield has been defined as the ratio between the volume flow of produced syngas (expressed in  $\text{Nm}^3/\text{h}$ ) and the mass flow of primary fuel (in  $\text{kg}/\text{h}$ ). In particular, for every kilogram of coal, about  $3.7 \text{ Nm}^3$  of syngas can be produced (except for Sulcis coal, in which syngas production is lower, due to the lower steam consumption).

Finally,  $\text{H}_2\text{S}$  and  $\text{COS}$  concentration in the raw syngas is strongly influenced by the sulphur content in the primary fuel. In any case, the experimental tests shown that a little amount of this sulphur (in particular for Sulcis coal) is detained by the bottom ash.

The laboratory scale gasifier is equipped with a series of 11 thermocouples, located near the vertical axis of the reactor in order to measure the temperature in the different operating zones: freeboard, coal heating, drying and devolatilization, pyrolysis, combustion and gasification [13-14].

Figure 3 shows the temperature profile into the laboratory scale reactor, fed with low sulphur South African coal. In particular, the three blue lines (curves 1, 2 and 3) correspond to three different phases of the gasifier start-up process, while phase 4 (black line) represents the steady-state operation condition. Temperature profile in phase 1 has been measured 20 minutes later the start of the three ceramic lamps which heat the start-up fuel before air injection; after other 20 minutes, the maximum temperature reaches the value of about  $550^\circ\text{C}$  (phase 2), while in phase 3 (100 minutes later the start of the lamps) the combustion and gasification reactions are in progress. The steady state (phase 4) has been reached about 150 minutes later the start of combustion and gasification reactions.

Figure 4 shows the temperature profile into the gasifier in two particular operating conditions, compared with the steady-state (curve a, which corresponds to “phase 4” in figure 3). Curve b represents the temperature profile few minutes after the charging of coal; it is possible to notice that the temperature in the combustion and gasification zone is about constant, but a significant temperature decreasing takes place in the upper zone of the reactor, where the fresh coal begins its heating and devolatilisation process. On the other hand, line c shows the temperature profile during a malfunctioning of the gasifier; the impossibility to operate ash discharging through the grate involved an ash stratification during the final phase of the plant run. Therefore, the combustion and gasification zone moves away from the grate, leaving a

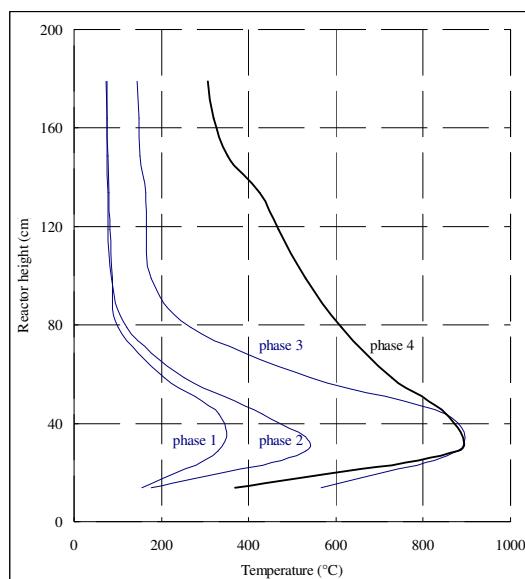


Fig. 3. Temperature profile during plant start-up.

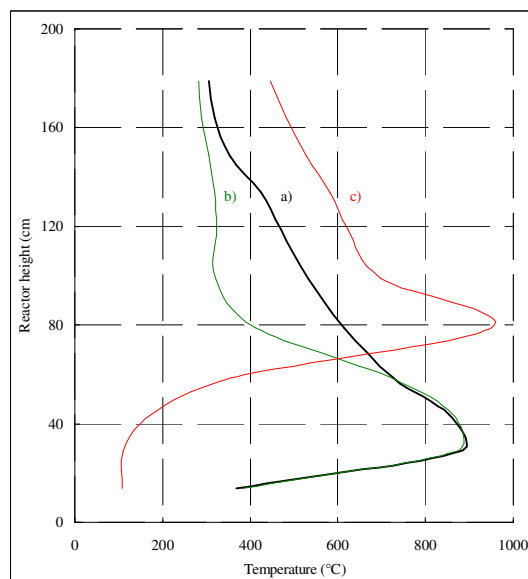


Fig. 4. Effects of coal inlet and ash stratification.

thick ash layer which is cooled by the cold gasification agents [15]. In this condition, the gasifier works far from its optimal conditions and a significant variation of syngas composition can be noticed. As a matter of facts, the gasification agents (air and steam), injected through the grate in the bottom of the reactor, reach with difficult the combustion and gasification zone, due to the formation of preferential paths. Moreover, the rising temperature in the upper part of the fuel bed and in the freeboard reduce the effect of the CO-shift conversion, with a subsequently reduction of the hydrogen content in the raw syngas [16].

Raw syngas composition is strongly conditioned by the gasification parameters and, in particular, by the air/coal and steam/coal mass ratios. The optimization of both these parameters has been one of the main goals of the experimental tests in the gasifier, and it is a consequence of the considered primary fuel and the load of the reactor.

Figures 5 and 6 show the effects of air/coal and steam/coal mass ratios, respectively, on the raw syngas composition (and, in particular, on hydrogen, carbon monoxide and carbon dioxide concentrations), with reference to the gasification of low sulphur South African coal.

As shown in figure 5, an increasing of the air/coal mass ratio involves a reduction of hydrogen and carbon monoxide concentrations, while carbon dioxide remains about constant. This is mainly due to the combination of two different phenomena: the rising temperature into the reactor (due to the higher amount of coal which is burnt from oxygen) reduces the effects of the CO-shift conversion, with a subsequent rise of CO content and a decreasing of H<sub>2</sub> and CO<sub>2</sub> concentration; on the other hand, the rising nitrogen content dilutes the raw syngas, thus reducing the concentration of the considered chemical species. As for hydrogen and carbon monoxide, both these phenomena involve a reduction of their concentration, while the CO<sub>2</sub> content remains about constant because the reduced effect of CO-shift reaction and the syngas dilution in nitrogen are offset by the higher amount of burnt carbon.

Figure 6 shows the effect of steam/coal mass ratio on raw syngas composition. 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<sub>2</sub> content due to the CO-shift reaction is offset by the syngas dilution in steam.

The results shown in figures 5 and 6 slightly differs by the “standard conditions” reported in table 2, being referred to different experimental runs (moreover, the standard conditions are averaged during a two hours steady state operation, as already mentioned).

Finally, one of the next phase of the experimental tests in the laboratory scale gasifier is to analyse the effects of air enrichment in oxygen on syngas composition and on gasification

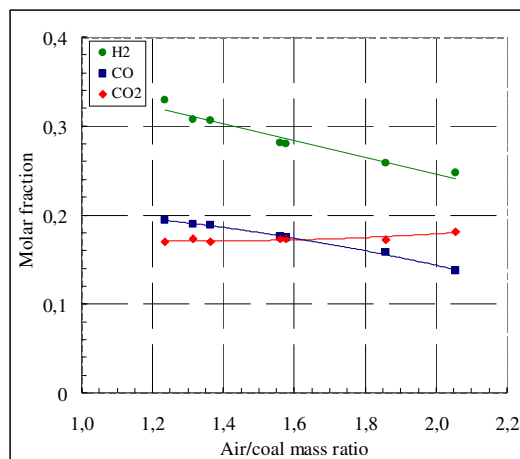


Fig. 5. Effects of air/coal mass ratio.

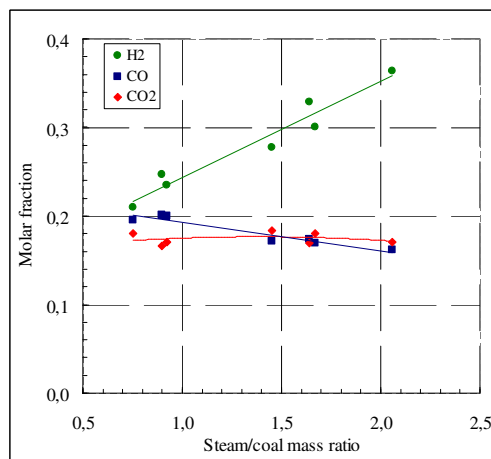


Fig. 6. Effects of steam/coal mass ratio.

performances. As a matter of fact, a rising of oxygen concentration in the oxidant agent involves a reduction of syngas dilution with nitrogen and, as a consequence, a decreasing of the syngas flow with a contemporary rising of its lower heating value. In this case, with reference to the industrial application of the technology, the syngas treatment line can be designed for a lower syngas flow, with a subsequently reduction of the capital and operating costs [15].

## 4 A global laboratory scale plant balance

In this section, a global mass balance of the Sotacarbo laboratory scale plant is presented, with the goal to evaluate the global plant performance in terms of hydrogen and electrical energy production. The analysis here reported has been 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 the flows have been determined with good accuracy.

Figure 7 and table 3 show the main results of this evaluation, with reference to the gasification of low sulphur South African coal. For each section of the plant (schematized in figure 7), the main properties of every streams have been reported. In particular, table 3 shows, stream by stream, the mass and volume flow, pressure, temperature, lower heating value (LHV) and specific heat, together with the gaseous streams composition, in terms of molar fractions. Is important to notice that the raw syngas composition differs to that reported in table 2, being the latter referred to dry syngas.

In order to give an idea on the hydrogen balance, figure 7 reports, for every stream, the mass flow (in kg/h) and the lower heating value (in MJ/kg), together with the molar flow of molecular hydrogen effectively contained and the molar flow of equivalent  $H_2$  (both expressed in mol/h of  $H_2$ ). In particular, the molar flow of equivalent  $H_2$  is the global amount of hydrogen contained in the chemical species ( $H_2$ ,  $CH_4$ ,  $H_2S$  and steam), which potentially can contribute to the overall hydrogen production. As a matter of facts, according with this definition, the global balance of  $H_2$  is influenced by the steam injection and condensation, by the hydrogen content in coal and, slightly, by the air moisture.

In parallel, figure 8 and table 4 show the results of the same analysis referred to the high sulphur Sulcis coal.

In the gasification section, hydrogen is mainly provided by the steam, used as gasification agent and, secondly, by coal (considered with its humidity). Raw syngas is characterized by a  $H_2$  concentration of about 32-34% and, globally, 2829 mol/h of equivalent  $H_2$  are treated, with reference to syngas from low sulphur coal.

This amount slightly variates through the skid (composed by the wet scrubber, the first cold gas desulphurization stage and the electrostatic precipitator), due to the balance between water injection and steam condensation (syngas from the skid is saturated at 50 °C). In particular, for syngas from low sulphur coal a decreasing of the molar flow of equivalent  $H_2$  takes places, due to the significant steam condensation, which involves a reduction of the global mass flow. On the other hand, when high sulphur coal is gasified, the molar flow of equivalent  $H_2$  rises through the wet scrubber, due to the lower steam content in raw syngas which involves a water evaporation; the global syngas mass flow slightly decreases because the evaporation is offset by the significant  $H_2S$  and  $CO_2$  absorption in the first desulphurization stage.

Through the cold gas desulphurization system, the molar flow of equivalent  $H_2$  decreases due to the steam condensation, being the syngas final temperature 30 °C. Globally, if all produced syngas is sent to the power generation line, about 2500 mol/h of equivalent  $H_2$  can be sent to the internal combustion engine, with reference to the gasification of low sulphur coal.



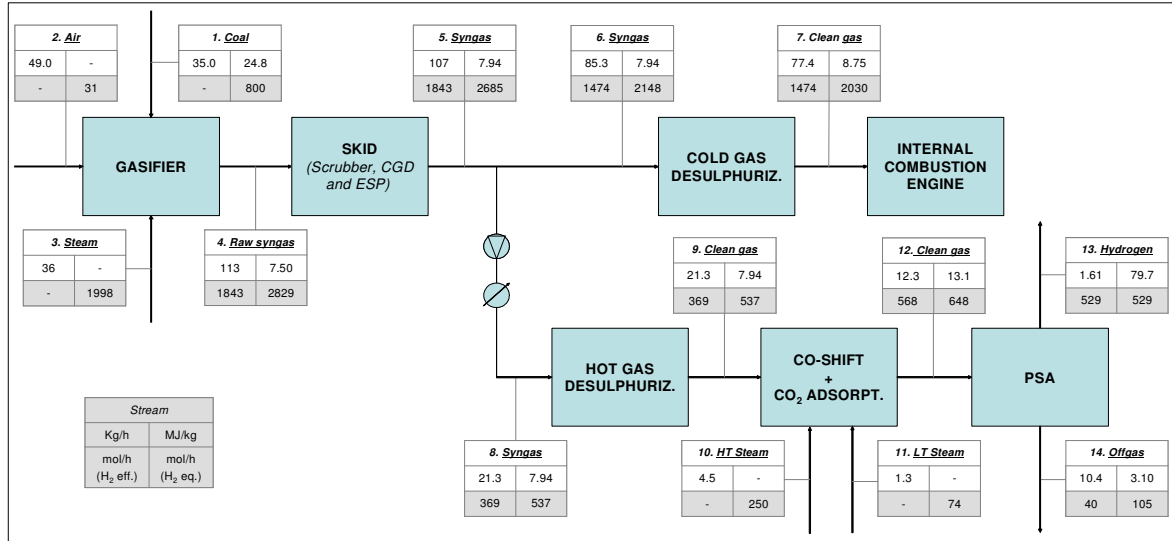


Fig. 7. Hydrogen production from low sulphur South African coal.

Table 3a. Stream properties and composition with South African coal.

	1 Coal	2 Air	3 Steam	4 Raw gas	5 Syngas	6 Syngas	7 Clean gas
Mass flow (kg/h)	35.00	49.00	36.00	112.89	106.58	85.26	77.37
Volume flow (Nm <sup>3</sup> /h)	-	38.18	44.79	128.57	123.53	98.83	90.23
Pressure (bar)	1.40	1.40	1.40	1.07	1.01	1.01	1.01
Temperature (°C)	25	75	120	300	50	50	30
LHV (MJ/kg)	24.79	-	-	7.50	7.94	7.94	8.75
Specific heat (kJ/kg·K)	0.13	1.01	1.67	1.55	1.57	1.57	1.57
Stream composition (molar fraction)							
CO	-	0.0000	0.0000	0.1935	0.2014	0.2014	0.2206
CO <sub>2</sub>	-	0.0000	0.0000	0.0968	0.0856	0.0856	0.0844
H <sub>2</sub>	-	0.0000	0.0000	0.3213	0.3345	0.3345	0.3662
O <sub>2</sub>	-	0.2057	0.0000	0.0000	0.0000	0.0000	0.0000
N <sub>2</sub>	-	0.7672	0.0000	0.2311	0.2405	0.2405	0.2634
CH <sub>4</sub>	-	0.0000	0.0000	0.0173	0.0180	0.0180	0.0198
H <sub>2</sub> S	-	0.0000	0.0000	0.0009	0.0000	0.0000	0.0000
COS	-	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001
H <sub>2</sub> O	-	0.0180	1.0000	0.1363	0.1171	0.1171	0.0424
Ar	-	0.0091	0.0000	0.0027	0.0028	0.0028	0.0031

Table 3b. Stream properties and composition with South African coal.

	8 Syngas	9 Clean gas	10 HT Steam	11 LT Steam	12 Clean gas	13 Hydrogen	14 Offgas
Mass flow (kg/h)	21.31	21.31	4.50	1.33	12.30	1.61	10.43
Volume flow (Nm <sup>3</sup> /h)	24.71	24.71	5.60	1.66	21.58	12.23	9.04
Pressure (bar)	1.40	1.40	2.40	2.40	1.29	1.40	1.01
Temperature (°C)	450	450	350	250	35	45	25
LHV (MJ/kg)	7.94	7.94	-	-	13.09	79.71	3.10
Specific heat (kJ/kg·K)	1.57	1.57	1.67	1.67	2.36	10.12	1.17
Stream composition (molar fraction)							
CO	0.2014	0.2015	0.0000	0.0000	0.0231	0.0081	0.0441
CO <sub>2</sub>	0.0856	0.0856	0.0000	0.0000	0.0458	0.0081	0.0985
H <sub>2</sub>	0.3345	0.3345	0.0000	0.0000	0.5904	0.9689	0.0987
O <sub>2</sub>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N <sub>2</sub>	0.2405	0.2405	0.0000	0.0000	0.2754	0.0146	0.6378
CH <sub>4</sub>	0.0180	0.0180	0.0000	0.0000	0.0207	0.0000	0.0493
H <sub>2</sub> S	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COS	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H <sub>2</sub> O	0.1171	0.1171	1.0000	1.0000	0.0414	0.0000	0.0643
Ar	0.0028	0.0028	0.0000	0.0000	0.0032	0.0003	0.0073



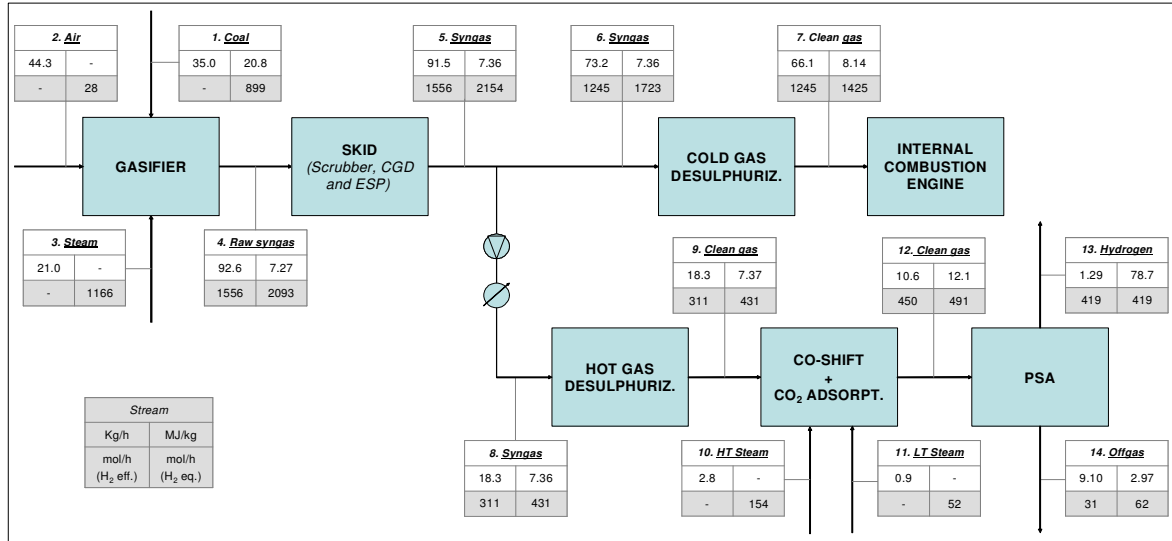


Fig. 8. Hydrogen production from high sulphur Sulcis coal.

Table 4a. Stream properties and composition with Sulcis coal.

	1 Coal	2 Air	3 Steam	4 Raw gas	5 Syngas	6 Syngas	7 Clean gas
Mass flow (kg/h)	35.00	44.35	21.00	92.59	91.46	73.17	66.10
Volume flow (Nm <sup>3</sup> /h)	-	34.56	26.13	102.04	104.51	83.16	76.05
Pressure (bar)	1.40	1.40	1.40	1.07	1.01	1.01	1.01
Temperature (°C)	25	75	120	270	50	50	30
LHV (MJ/kg)	20.83	-	-	7.27	7.36	7.36	8.14
Specific heat (kJ/kg·K)	0.19	1.01	1.67	1.51	1.55	1.55	1.56
Stream composition (molar fraction)							
CO	-	0.0000	0.0000	0.1694	0.1654	0.1654	0.1819
CO <sub>2</sub>	-	0.0000	0.0000	0.1228	0.1020	0.1020	0.1009
H <sub>2</sub>	-	0.0000	0.0000	0.3420	0.3337	0.3337	0.3667
O <sub>2</sub>	-	0.2057	0.0000	0.0000	0.0000	0.0000	0.0000
N <sub>2</sub>	-	0.7672	0.0000	0.2635	0.2571	0.2571	0.2827
CH <sub>4</sub>	-	0.0000	0.0000	0.0196	0.0192	0.0192	0.0211
H <sub>2</sub> S	-	0.0000	0.0000	0.0117	0.0001	0.0001	0.0000
COS	-	0.0000	0.0000	0.0012	0.0008	0.0008	0.0009
H <sub>2</sub> O	-	0.0180	1.0000	0.0667	0.1187	0.1187	0.0425
Ar	-	0.0091	0.0000	0.0031	0.0030	0.0030	0.0033

Table 4b. Stream properties and composition with Sulcis coal.

	8 Syngas	9 Clean gas	10 HT Steam	11 LT Steam	12 Clean gas	13 Hydrogen	14 Offgas
Mass flow (kg/h)	18.29	18.26	2.77	0.93	10.59	1.29	9.10
Volume flow (Nm <sup>3</sup> /h)	20.90	20.88	3.44	1.16	17.79	9.69	7.87
Pressure (bar)	1.40	1.40	2.40	2.40	1.29	1.40	1.01
Temperature (°C)	450	450	350	250	35	45	25
LHV (MJ/kg)	7.36	7.37	-	-	12.15	78.68	2.97
Specific heat (kJ/kg·K)	1.55	1.55	1.67	1.67	2.26	10.02	1.17
Stream composition (molar fraction)							
CO	0.1654	0.1664	0.0000	0.0000	0.0195	0.0072	0.0354
CO <sub>2</sub>	0.1020	0.1020	0.0000	0.0000	0.0443	0.0081	0.0904
H <sub>2</sub>	0.3337	0.3332	0.0000	0.0000	0.5669	0.9678	0.0900
O <sub>2</sub>	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
N <sub>2</sub>	0.2571	0.2574	0.0000	0.0000	0.3022	0.0166	0.6644
CH <sub>4</sub>	0.0192	0.0192	0.0000	0.0000	0.0225	0.0000	0.0511
H <sub>2</sub> S	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
COS	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H <sub>2</sub> O	0.1187	0.1188	1.0000	1.0000	0.0411	0.0000	0.0611
Ar	0.0030	0.0030	0.0000	0.0000	0.0035	0.0003	0.0076

The amount of equivalent  $H_2$  remains constant through the hot gas desulphurization system (for both high and low sulphur coals,  $H_2S$  concentration downwards the first cold gas desulphurization stage is very low). The integrated CO-shift and  $CO_2$  capture section is characterized by two different steam injection (upwards the high and the low temperature CO-shift stages) and by a series of syngas coolers, which involve a condensation of a significant amount of steam. Globally, syngas is enriched in hydrogen, with a final  $H_2$  concentration of about 57-59% and a global amount of equivalent  $H_2$  of 648 and 491 mol/h for syngas from low and high sulphur coal, respectively.

Finally, through PSA section, a large part of this amount (529 mol/h, with reference to the gasification of low sulphur coal) is separated as hydrogen-rich stream (with a purity of about 97%), while the remaining 119 mol/h can be found in the offgas and in a little amount of condensate.

Globally, in the Sotacarbo coal-to-hydrogen experimental plant (in which only 20% of the produced syngas is sent to the hydrogen production line), 35 kg/h of coal allow to produce about 1.3-1.6 kg/h of hydrogen. Obviously, the most significant contribution in hydrogen production comes from the gasification steam. If all syngas should be sent to the 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).

## 5 Conclusions

The experimental tests carried out in the Sotacarbo laboratory scale coal-to-hydrogen plant allowed both to obtain some data and to evaluate the performances of each plant section. The conventional processes used for the 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 an hydrogen stream with a purity of about 97% suitable for the use in an internal combustion engine. Even if this purity is relatively low with respect to the current state of the art in hydrogen purification processes, it is possible to obtain a very high purity hydrogen (up to 99.999%) by using a more sophisticated PSA process when the technology will be scaled-up to an industrial application for distributed power generation.

The cold gas desulphurization technology 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. On the other hand, the hot gas desulphurization system (based on zinc oxides as sorbent) allows to obtain an  $H_2S$  concentration lower than 10 ppm (and, in many cases, lower than 1 ppm) in the clean syngas. These concentrations are compatible with some technologies for distributed power generation, like internal combustion engine, micro gas turbines and different kinds of fuel cell.

Moreover, the experimental tests demonstrate that the carbon dioxide emissions can be strongly reduced (up to 85-90% without solvent recirculation) through the capture plant, which currently doesn't include a solvent regeneration system; with reference to an industrial application of the technology, a capture system equipped with a solvent regeneration section and a carbon sequestration plant will allow to separate and store more than 90-95% of the global carbon content, with some economical advantages related with the International Emissions Trading.

During the experimental tests, an 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<sup>3</sup> per kilogram of coal, to be compared with 1.38 Nm<sup>3</sup> obtained for high sulphur Sulcis coal.

Syngas cleaning systems have a low influence on the hydrogen content in syngas, which is mainly determined by the gasification conditions and by the performances of the CO-shift process. The molar flow of equivalent H<sub>2</sub> can be considered as a performance indicator for the evaluation of the production efficiency. In particular, reporting the scale of the hydrogen production line to that of the gasification process (35 kg/h), 2829 mol/h of equivalent hydrogen can be produced by the gasification of low sulphur coal, while 1620 mol/h are injected through steam into the CO-shift process; about 40.5% of this equivalent hydrogen can be found downwards PSA. As for the gasification of high sulphur Sulcis coal, about 33% of the entering hydrogen can be separated by PSA.

Obviously, in the Sotacarbo laboratory scale plant the hydrogen production has not been optimized, due to the experimental aim of the plant. This justifies the relatively high energy content in the offgas, which, in the experimental plant, is 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 the hydrogen production (thus reducing the energy content in the offgas) or to reduce hydrogen production and use the offgas for the co-production of electrical energy.

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