Chapter 2

AN OVERVIEW ABOUT CURRENT AND FUTURE EXPERIMENTAL ACTIVITIES IN A FLEXIBLE GASIFICATION PILOT PLANT

Alberto Pettinau^{*}, Francesca Ferrara and Carlo Amorino

Sotacarbo S.p.A. - c/o Grande Miniera di Serbariu - 09013 Carbonia - ITALY

ABSTRACT

In the field of hydrogen production through coal gasification for distributed power generation, Sotacarbo, an Italian limited company which operates in the field of clean coal technologies, is developing different research and development projects for the tuning of a coal-to-hydrogen process configuration. Toward this goal, a flexible pilot platform was built in 2007-2008, and it is currently in operation. In particular, the platform includes demonstrative and pilot air-blown fixed-bed gasifiers, the latter equipped with a flexible syngas treatment line for a combined power generation and CO_2 -free hydrogen production.

This chapter presents a detailed description of all the experimental equipment and the main results obtained during the first 700 hours of tests in the pilot unit. In particular, the optimum operating conditions with a low sulphur South African coal have been defined, with a syngas production of about 43 Nm³/h (from the gasification of 8 kg/h of coal), characterized by a lower heating value of 4.5 MJ/kg, and a high cold gas efficiency, of about 97%.

A series of experimental tests has also been carried out in order to assess the plant performance under different operating conditions and the effects of the main parameters, such as air/fuel and steam/fuel mass ratios and oxidant composition (air, eventually enriched in oxygen, or mixtures of oxygen and carbon dioxide). Moreover, a series of preliminary tests has been carried out in order to evaluate the gasification performance with a portion of high sulphur Sulcis coal or biomass (wood pellets) in the fuel blend.

The experimental results obtained in syngas treatment processes show a very efficient removal of pollutants (in particular, a final concentration of sulphur compounds lower than 10 ppm, in volume, can be obtained, even with high sulphur coal in the fuel

^{*} Corresponding author: apettinau@sotacarbo.it

blend) and the possibility to reduce carbon dioxide emissions of about 90% by using a single-stage amine-based carbon capture system, which assures a CO_2 absorption efficiency of about 99%.

Finally, the guidelines of the future research activities are described in this chapter, with particular reference to the further optimization of both gasification and syngas treatment processes in different operating conditions.

1. INTRODUCTION

In a long-term view for the future, a strong development of all the technologies based on renewable and nuclear energy sources can be expected due to the need of increasing energy production and to mitigate greenhouse gas emissions [1-2]. In the meantime, sustainable energy production needs further significant effort toward the reduction of energy consumption and toward the development of high efficiency fossil fuels-based power generation plants, equipped with carbon capture and storage (CCS) systems [3]. Moreover, due to its great price stability¹, coal represents a secure and feasible primary fuel for the production of electrical energy [4-5] and different energy carriers, such as hydrogen.

Among clean coal technologies, coal gasification could represent a competitive option for power generation. According to a recent study published by the European Commission [6], power generation through integrated gasification combined cycles (IGCC) currently involves a production cost of electricity (CoE) slightly higher than those corresponding to a conventional pulverized coal combustion (PCC) plant². This difference tends to be reduced according to the projection for 2020, and IGCC becomes convenient with respect to PCC if a CCS configuration is considered³. As a matter of fact, the possibility to operate carbon capture from syngas before the combustion process (in general by using cold gas chemical absorption processes with alkanolamine solutions [7-9]), allows for operation with a relatively low gas flow and a relatively high CO₂ partial pressure, with subsequent advantages in terms of removal efficiency and equipment size [3].

Moreover, compared to combustion technologies, coal gasification allows the production of chemicals or clean fuels, with particular reference to hydrogen [10-12], universally considered one of the most important energy carriers [13-15] and characterized by a worldwide production (18% from coal) greater than one billion of cubic meters per day [16-18].

In this context, Sotacarbo⁴ is engaged in a series of research and development projects in order to develop and optimize a coal gasification process and an integrated syngas treatment

¹ Compared to oil and natural gas, whose main fields are confined to a relatively small area, coal is widely available in the world and distributed more uniformly than other fossil fuels; this allows a great price stability and represents a secure source from a strategic point of view.

² The evaluation, referred to year 2007, indicates a CoE of 45-55 €/MWh for IGCC and CFBC (circulating fluidized bed combustion) plants and of 40-50 €/MWh for conventional PCC plants.

³ The projection for the year 2020 indicates a CoE of 75-90 €/MWh for IGCC and 80-105 €/MWh for PCC, both equipped with a carbon capture and storage system.

⁴ Sotacarbo S.p.A. is a limited company controlled by the Sardinian Regional Administration and by ENEA, the Italian National Agency for Energy and Environment; established in 1987, it operates research and development in the field of clean coal technologies. Currently Sotacarbo, with the aid of its research center and

line for hydrogen production from coal. Toward this goal, a flexible pilot platform has been built at the Sotacarbo Research Centre, in Carbonia (South-West Sardinia, Italy).

The choice of the configuration of the pilot platform is a compromise between the need to develop a coal gasification process for medium and small scale industrial applications and the interest in the development of coal-to-hydrogen integrated processes to be applied in large-scale power plants.

In particular, the target of the gasification process (medium and small scale, up to 10-15 MW_{th}) led the choice of a fixed-bed, air-blown gasifier. As a matter of fact, these processes can be simply managed [19-20], and it is well known that the counter current fluid dynamics assure a higher efficiency with respect to other gasification technologies [21-22]. Moreover, the selected gasification technology allows a great flexibility in terms of primary fuel (different kinds of coal and also biomass and wastes).

A typical large-scale coal-to-hydrogen plant configuration could include, for example, an oxygen-blown entrained-flow gasification process, operating at high pressure; the scale down of such a process to pilot scale involves a series of technical problems. Therefore, the need to analyze a hydrogen production line from coal syngas suggested use of the same fixed-bed gasifier as syngas producer, even if the raw syngas properties are quite different with respect to those produced in a typical large scale plant. This choice allowed a significant reduction of the research costs and strongly simplified the management of the plant.

This chapter reports a detailed description of the whole pilot platform, together with an overview of the main experimental results obtained during about 700 hours of experimental tests. Moreover, a description of the potential research activities which could be carried out in the pilot platform is here presented.

2. THE SOTACARBO PILOT PLATFORM

The Sotacarbo pilot platform was built in 2007-2008 (in the field of a research and development project⁵ partially funded by the Italian Ministry of Education and Research) to test different plant solutions and different operating conditions; therefore, a very flexible and simple layout was selected during the design and construction phases.

Currently, the layout of the Sotacarbo pilot platform (figure 1) includes two fixed-bed updraft and air-blown gasifiers: a 700 kg/h (corresponding to about 5 MW_{th}) demonstrative unit and a 8-10 kg/h (about 80 kW_{th}) pilot unit. The choice of this kind of gasification process is a consequence of the particular commercial interest in the field of medium and small scale industrial applications.

Whereas the main goal of the experimental tests on the demonstrative unit is the optimization of the gasifier (in different operating conditions) for its commercialization, the pilot plant is mainly used to study and develop the gasification and syngas treatment

its laboratories, is mainly engaged in research activities on coal gasification, hydrogen production and near zero emissions power generation.

⁵ The project, called COHYGEN (coal-to-hydrogen generation), started in 2003 and it has been concluded in early 2009, with a total cost of about 11 M€; partner of the project were Ansaldo Energia (former Ansaldo Ricerche), ENEA and the Department of Mechanical Engineering of the University of Cagliari.

processes for a combined production of hydrogen and electrical energy. Therefore, the pilot plant is equipped with a complete and flexible syngas treatment process.



Figure 1. The Sotacarbo pilot platform.

2.1. Demonstrative unit

The demonstrative unit is based on a 5 MW_{th} gasifier (figure 2), equipped with a manual coal charging system, a wet scrubber for dust and tar (topping atmospheric residue) removal and a flare for syngas combustion.

For the feed of the gasifier, coal (characterized by a granulometry between 5 and 60 mm, according to the design conditions) is bought in big bags for the experimental tests; every bag, containing about 1 ton of coal, is drawn out from the storage area by a heaver and, through a tackle, charged in a proper hopper in order to empty the bag itself. Then, coal is drawn out from this hopper and sent to the gasifier through four different injection points in order to distribute the fuel as uniformly as possible and to optimize the gasification process.

The reactor is similar to Wellman-Galusha gasifiers and operates at about atmospheric pressure (0.11-0.14 MPa). Being a fixed-bed reactor, the fuel bed is characterized by different operating zones, where the coal drying, devolatilization, pyrolisis, gasification and combustion processes take place. As coal flows downwards, it is heated by the hot raw gas that moves upwards, coming from the gasification and combustion zones [23-24]. The gasification agents (air and steam) are introduced into the reactor near the bottom, below the fuel grate, so that they are pre-heated by the cooling bottom ashes, which are removed through the grate itself.

In order to distribute the fuel as uniformly as possible, the reactor is equipped with a stirrer (internally cooled, in order to keep a low metal temperature), which is characterized by two degrees of freedom: an axial rotation and a vertical translation [25]. Furthermore, the

gasifier is equipped with a cooling water jacket, in order to operate an accurate temperature control (figure 3).



Figure 2. Demonstrative gasifier.



Figure 3. Simplified scheme of the demonstrative gasifier.

The start-up of the gasifier is carried out by using a series of three ceramic lamps, located near the bottom of the fuel bed, which heat the fuel (initially wood pellets) in an inert atmosphere. When the temperature reaches about 800-850 °C, air is injected into the reactor and the fuel combustion takes place. Finally, steam is also injected into the reactor (whereas, in the meantime, air injection is reduced to sub-stoichiometric conditions) and coal can be fed as gasification fuel. As for the temperature control, the gasifier is equipped by a series of 36 thermocouples (6 sensors, disposed around the circular section of the reactor, in 6 different height levels) in order to have a detailed temperature profile of the reactor.

The pilot plant does not include a syngas desulphurization section (raw syngas is only sent to a wet scrubber, for tar and dust removal, and then it is directly burned in a flare); therefore, it can be only fed with fuels characterized by a sulphur content lower than 0.5-0.6 % (in weight).

The experimental tests on the demonstrative plant have not been started as of when this chapter was prepared. In any case, a global syngas production of about 2500 Nm³/h can be estimated (through the use of a mathematical model of the process). The expected raw syngas lower heating value is about 6.5 MJ/kg, with a hydrogen concentration of about 21%; it corresponds to a cold gas efficiency of 93-94%.

2.2. Pilot unit

The pilot unit, in which the experimental tests reported in this chapter have been carried out, were developed in order to study and optimize the gasification process and to produce a syngas flow to feed the experimental syngas treatment process for combined production of hydrogen and electrical energy.

Gasification process

Due to its dimension, the pilot gasifier (figure 4) is quite different from the demonstrative unit. In particular, whereas the 5 MW_{th} unit is cooled through a water jacket, the walls of the pilot gasifier are covered with a refractory material; moreover, coal is charged through a single inlet point and the reactor is not equipped with the intercooled stirrer. The fuel bed is held up by a grate which includes two series of metallic bars: the upper one is fixed and directly in contact with fuel, whereas in the lower one each bar is equipped with two blades and can rotate around its axis, thus increasing or reducing the openings. The temperature profile of the reactor can be determined through a series of 11 thermocouples disposed over a metallic probe (which can operate up to 1200 °C) inserted through the top of the gasifier and located near the reactor vertical axis. Each temperature sensor is about 150 or 200 mm (depending on the position into the reactor) far from each other.

The manually controlled fuel feeding system is identical with respect to the demonstrative plant and an extractor fan, which serves both pilot and demonstrative gasifiers, allows the extraction of dust during the coal handling and charging phases. As for the plant start-up, a series of three ceramic lamps allows the heat of the reactor, initially fed with wood pellets (with the addition of a small amount of paraffinic material, in order to promote the ignition) and subsequently charged with coke (only when the gasification reactions are running the coal is fed to the reactor).



Figure 4. Pilot gasifier.

Dust and tar removal system

As can be seen in the pilot plant simplified scheme (figure 5), raw syngas from the gasification process is sent to an integrated component which includes a wet scrubber, a first cold gas desulphurization stage and an electrostatic precipitator (ESP).

In particular, the wet scrubber reduces syngas temperature from 150-300 °C (depending on the particular operating conditions) to about 50 °C and operates a primary dust and tar separation. Sometimes, when fine particles and tar contents in raw syngas are very high⁶, the wet scrubber is not able to operate a fine removal of these components; in this case, the electrostatic precipitator can be used in order to strongly reduce particulate and tar content in syngas.

Finally, the need to use coal with a very high sulphur content and to protect the electrostatic precipitator from the effects of an acidic atmosphere, prompted the insertion, between wet scrubber and ESP, of a first cold gas desulphurization stage, which generally uses sodium hydroxide (40% in volume, diluted in water), as solvent for H_2S removal.

Downstream the ESP, syngas can be sent to the power generation line; moreover, depending on the goals of each experimental test, a portion of syngas (20-25 Nm^3/h) can be sent to the hydrogen production line.

⁶ Their concentration strongly depends on primary fuel and operating conditions. For example, the gasification of biomass or high volatiles coals involve a very high tar content in raw syngas.



Figure 5. Pilot plant simplified scheme.

Power generation line

The power generation line is constituted by the second cold gas desulphurization stage directly followed by an internal combustion engine (ICE), characterized by a nominal power output of about 24 kW, fed with clean syngas, eventually enriched in hydrogen.

In particular, the second cold gas desulphurization stage (figure 6) is a packed column, made of polypropylene (and filled with Rashig rings, made of the same material, with a diameter of 25 mm and disposed randomly), in which hydrogen sulphide is chemically absorbed through a proper solvent. According to the design conditions, syngas is washed with an aqueous solution of sodium hydroxide and hypochlorite (typically 40% and 13% in volume, respectively), according to the well-known following reactions [26]:

$$2NaOH + H_2S \Leftrightarrow Na_2S + 2H_2O \tag{1}$$

$$Na_{2}S + 4NaOCl \Leftrightarrow Na_{2}SO_{4} + 4NaCl$$
⁽²⁾

During some experimental tests, the packed column has been used with methildiethanolamine (MDEA) as solvent for H_2S absorption⁷.

Hydrogen production line

The hydrogen production line includes a compressor followed by an electric heater, a dry hot gas desulphurization process, an integrated water-gas shift (WGS) and CO_2 absorption system and a hydrogen purification section.

 $^{^{7}}$ The packed column designed as second cold gas desulphurization stage has been also used, during a series of experimental tests, as CO₂ absorber with different amine-based solutions.

In particular, the hot gas desulphurization process (figure 7) operates at about 300-500 $^{\circ}$ C and includes three main components: a catalytic filter for COS conversion and two H₂S adsorbers.



Figure 6. Second cold gas desulphurization stage.

In the catalytic filter, the small amount of carbonyl sulphide contained in syngas reacts with hydrogen to be converted to H_2S , according with the hydrogenation reaction [27]:

$$COS + H_2 \Leftrightarrow H_2S + CO$$
 (3)

promoted by Ni-MoO₃/Al₂O₃ catalyst.

On the other hand, the two hydrogen sulphide absorbers are disposed in lead-leg configuration and filled with a zinc oxide-based sorbent [28-30]: zinc oxide (ZnO) reacts with H_2S producing zinc sulphide and steam, according with the following reaction [31-33]:

$$ZnO + H_2S \Leftrightarrow ZnS + H_2O \tag{4}$$

The integrated water-gas shift and CO_2 separation system includes both high and low temperature shift reactors with an intermediate and a final CO_2 absorber.

In particular, the WGS process takes place in two reactors (operating at 300-450 °C and about 250 °C, respectively) which have been installed in order to test different catalysts, including conventional Fe₃O₄/Cr₂O₃/CuO based catalysts for high temperature (HT) stage and

 $CuO/ZnO/Al_2O_3$ based catalysts for low temperature (LT) stage [34-36]; toward this goal, the reactors have been designed with a maximum bed volume of 9.6 and 17.5 dm³, respectively.



Figure 7. Hot gas desulphurization system.

Conventional catalysts require lengthy in situ pre-reduction; they are sensitive to air (pyrophoric) and condensed water, and are poisoned by sulphur [37]. In order to avoid these kinds of problems, as of now the water-gas shift section has been tested with advanced non pyrophoric commercial catalysts. In particular, the high temperature catalyst is composed of cylindrical pellets with particles of platinum deposed in a matrix of zirconium doped ceria; on the other hand, the low temperature catalyst is composed of spherical particles with a matrix of alumina with zirconium, cerium and lanthanum and an external surface composed of the same elements with the addition of carbon and platinum [37-38].

Carbon dioxide absorption takes place in two identical bubbling reactors (figure 8), made of AISI 316L, in which syngas is injected through 40 diffusers based on ceramic membranes and reacts, at about 30 °C and atmospheric pressure, with amine-based solvents.



Figure 8. CO₂ absorbers.

In particular, different solvents, such as monoethanolamine (MEA) in different concentrations and a solution of methyldiethanolamine (MDEA) and piperazine (PZ), have been used in this process in some experimental tests. In particular, according to the design conditions, a 5M (about 30% in weight) aqueous solution of monoethanolamine reacts with CO_2 in accordance with the following well-known mechanism [39-44] where R in equation (9), (10) and (11) represents CH_2 - CH_2OH :

$2H_2O \Leftrightarrow OH^- + H_3O^+$	(ionization of water)	(5)
$CO_2 + 2H_2O \Leftrightarrow HCO_3^- + H_3O^+$	(CO ₂ hydration)	(6)
$HCO_3^- + H_2O \Longleftrightarrow CO_3^{2-} + H_3O^+$	(dissociation of bicarbonate)	(7)
$CO_2 + OH^- \Leftrightarrow HCO_3^-$	(formation of bicarbonate)	(8)
$CO_2 + 2RNH_2 \Leftrightarrow RNHCOO^- + RNH_3^-$	(reaction of CO ₂ with MEA)	(9)
$RNH_{2}^{+} + H_{2}O \Leftrightarrow RNH_{2} + H_{2}O^{+}$	(dissociation of protonated MEA)	(10)

$$RNHCOO^{-} + H_2O \Leftrightarrow RNH_2 + HCO_3^{-}$$
(carbamate to bicarbonate reversion) (11)

Finally, the hydrogen purification section is based on the pressure swing adsorption (PSA) technology, which is widely common in the industrial applications due to its low costs [10]. In particular, PSA is composed of a simple double-stage process based on carbon molecular sieves.

The size of the secondary syngas treatment line, even if much smaller than the size of commercial scale plants, has been chosen in order to give reliable experimental data for the scale-up of future plants.

Moreover, with the goal being 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.

2.3. Control system and data collection

In order to support the experimental tests, the pilot plant is equipped with a control and sampling system which allows monitoring of the process performance. In particular, process operation can be managed mainly through the control system, which automatically collects the main process parameters (such as pressures, temperatures, volume flows and so on).

As for syngas composition and properties, 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 of the gasification process). Moreover, upstream and downstream of each plant component, a sampling outlet has been placed in order to operate syngas analysis through a gas chromatograph and to evaluate the concentration of the main chemical compounds (CO₂, H₂, O₂, CO, CH₄, N₂, H₂S, COS, C₂H₆, C₃H₈) in the selected stream.

Finally, the plant has been recently equipped with a tar sampling and analysis system, in order to evaluate, through a proper gas chromatograph, the content and the composition of the main hydrocarbon components in raw syngas.

3. COAL GASIFICATION PERFORMANCE IN THE PILOT UNIT

Globally, the pilot gasifier has been tested for about 700 hours with different fuel blends. In particular, during the first experimental campaign (between June 2008 and March 2009) the gasifier was tested with operating parameters very far from the design conditions due to some technical problems, which were resolved in late 2009 through a series of plant modifications⁸. The last experimental campaign was mainly carried out in order to optimize the gasification process in its conventional operating condition. In particular, this chapter presents the main results obtained during this new campaign, with the experimental data collected during more than 400 hours of experimental tests carried out between December 2009 and September 2010.

3.1. "Standard" gasification performance

A great number of the experimental tests considered here have been operated using a low sulphur South African coal; the proximate, ultimate and thermal analyses, determined in the Sotacarbo laboratories (according with the international standard procedures), are shown in table 1. The same table also reports the characterization of a high sulphur Sulcis coal (extracted from the only Italian coal mine located in South-West Sardinia, near the Sotacarbo plant), which has been used (in mixture with South African coal) in some experimental tests.

During the first phase of the last experimental campaign, the plant operating conditions had been optimized in order to increase syngas production and lower heating value (LHV). In particular, a series of experimental tests has been carried out with different air/coal and steam/coal mass ratios, in order to analyze the effects of both these parameters on temperature profile and on syngas composition. The main result of all these tests is the definition of the "standard" operating conditions, which represent the best performance obtained by the gasification of only South African coal [45]. These results, shown in table 2, have been averaged during more than six hours of steady-state operation of the reactor.

Currently, the best performance of the pilot gasifier has been obtained with the injection of 36.8 kg/h of air and 6.0 kg/h of steam. In this way, the air-blown gasification of 8.0 kg/h of coal (corresponding to a thermal input of about 60 kW) involves the production of 43 Nm^3 /h of raw syngas, which is characterized by a lower heating value of 4.50 MJ/kg. In particular, coal consumption is significantly influenced by a series of parameters such as fuel reactivity, fuel resident time [46] and steam/coal and air/coal mass ratios.

Table 1. South African and Sulcis coal characterization.

⁸ The main plant modification is the replacement of the old grate of the gasifier (which gave some problems during the ash discharging phases) with a new one, directly designed by Sotacarbo.

	South African coal	Sulcis coal
Proxima	te analysis (% in weight)	
Fixed carbon	72.58 %	40.65 %
Moisture	3.64 %	7.45 %
Volatiles	8.81 %	40.45 %
Ash	14.97 %	11.45 %
Ultimat	e analysis (% in weight)	
Total carbon	75.56 %	66.49 %
Hydrogen	3.86 %	6.18 %
Nitrogen	1.40 %	1.41 %
Sulphur	0.57 %	7.02 %
Moisture	3.64 %	7.45 %
Ash	14.97 %	11.45 %
Ther	mal analysis (MJ/kg)	
Higher heating value	28.10	22.59
Lower heating value	27.18	21.07

Table 2. Synthesis of "standard" gasification conditions.

"Stande	ard" oper	ating parameters	
Primary fuel consur	nption (kg	g/h)	8.0
Air mass flow (kg/h)		36.8
Steam mass flow (k	g/h)		6.0
Dry synge	is compos	ition (molar ratio	s)
CO	0.1807	CH_4	0.0151
CO_2	0.0947	H_2S	0.0003
H_2	0.1889	COS	0.0001
N ₂	0.5128	O_2	0.0074
Gasifier performance			
Syngas mass flow (I	kg/h)		46.83
Syngas volume flow	v (Nm ³ /h)		42.90
Syngas lower heating value (MJ/kg)		4.50	
Specific heat (kJ/kg K)		1.23	
Syngas outlet pressure (MPa)		0.14	
Syngas outlet temperature (°C)		126	
Maximum reaction temperature (°C)		1034	
Cold gas efficiency		96.93%	
Hot gas efficiency		92.90%	
Gasifier yield (Nm ³	/kg)		5.36

Raw syngas is composed of a high nitrogen content (51%, in volume), typical of airblown gasification process [19, 47], and a relatively high hydrogen content (about 19%).

Cold gas efficiency is defined as the ratio between the chemical power associated with raw syngas and those associated with coal:

$$\eta_{CG} = \frac{m_G \cdot LHV_G}{m_C \cdot LHV_C} \tag{12}$$

where m_G and m_C are the mass flows of syngas and coal and LHV_G and LHV_C are the lower heating values of the same fuels, respectively. This value is very consistent with the corresponding typical efficiencies of the industrial air-blown fixed-bed gasification plants.

Hot gas efficiency represents a more detailed performance indicator of the gasification section, taking in account sensible heats, steam production and, eventually, mechanical work; in this case, it can be defined through the following simplified equation:

$$\eta_{HG} = \frac{m_G \cdot LHV_G + Q_G}{m_C \cdot LHV_C + Q_S} \tag{13}$$

where Q_G and Q_S are the thermal energy associated to produced syngas (sensible heat) and injected steam (the latter takes into account the inefficiencies of the steam production and injection system), respectively. This equation does not consider the steam production through syngas cooling and the mechanical work: both these terms are null in this gasification process.

Finally, gasifier yield is defined as the ratio between the volume flow of produced syngas, expressed in normal cubic meters per hour, and the mass flow of primary fuel, in kilograms per hour.

Raw syngas composition is strongly influenced by the primary fuel properties and the gasification parameters. In particular, raw syngas from South African coal (in "standard" conditions) presents a very low content of sulphur compounds (274.3 ppm of H₂S and 100.9 ppm of COS, both expressed in volume). This result can be compared with the sulphur content in raw syngas from the gasification of only Sulcis coal (characterized by a sulphur content of about 7% in weight), which typically amounts to about 12000 ppm.

Thermal profiles in the reactor are significantly variable during the process (even during the steady-state phases, when steam and air mass flow are about constant), due to being influenced by a series of parameters such as the succession of coal charging and ash extraction, both of which are discontinuous. Figure 9 shows the typical temperature profiles (measured by the previously described temperature probe located near the vertical axis of the reactor) in the pilot gasifier.

The three dotted lines correspond to three different steps of the gasifier start-up process, measured 30, 60 and 90 minutes after the start of air injection, respectively. On the other hand, the continuous line represents the temperature profile during the steady-state operation (reached about 120-180 minutes after the start of air injection), averaged during the same period that has been assumed to define the "standard" conditions.

In this figure it is possible to distinguish the different operating zones of the gasifier: the freeboard (between the top of the reactor and about 1200 mm from the bottom), in which temperature remains near uniform at 125-130 °C; the coal heating, drying, devolatilization and pyrolisis zone (800-1200 mm); the combustion and gasification zone (100-800 mm, in which the maximum temperature of about 1000-1050 °C is reached) and the ash cooling area.

When fresh coal is charged into the reactor, a remarkable temperature decrease can be observed in the upper part of the fuel bed, whereas there are not appreciable variations of the thermal profile in the combustion and gasification zone. On the other hand, ash discharge involves a slight vertical translation of the thermal profile; in this case, the high temperature zone slightly moves down near the grate.



Figure 9. Temperature profiles into the gasifier.

3.2. Effects of air/coal mass ratio

Theoretically, an increasing of the air/coal mass ratio (with respect to the "standard" conditions) involves a reduction of hydrogen and carbon monoxide concentrations [19]. This is mainly due to the combination of three different phenomena: the rising temperature in the reactor, which reduces the effects of water-gas shift conversion; the increasing nitrogen content, which dilutes raw syngas; and, mainly, the effects of combustion reactions, promoted by the higher oxygen supplying.

On the other hand, the subsequent raising of steam injection⁹ promotes both the gasification and water-gas shift reactions (increasing the reactants concentration and reducing the operating temperature in the reactor) and involves a raising of hydrogen concentration and a decreasing of CO content; carbon dioxide concentration remains almost constant because the increase of CO_2 content due to the water-gas shift reaction is offset by the syngas dilution by steam [5].

⁹ In order to maintain the same temperature profile, in particular in the combustion and gasification zone, near the bottom of the gasifier, steam injection has been increased together with the raise of air/coal mass ratio.

Table 3 shows the effects of the raising air/coal mass ratio through a comparison between the gasification results in "standard" operating conditions and those obtained during the test run in which the maximum South African coal consumption has been obtained. Both tests were operated at the same maximum temperature (1000-1050 °C), controlled through a variation of steam injection.

	"Standard"	Max. cons.
Operating param	neters	
Primary fuel consumption (kg/h)	8.0	10.3
Air mass flow (kg/h)	36.8	45.0
Steam mass flow (kg/h)	6.0	10.0
Dry syngas composition	(molar ratios)	
СО	0.1807	0.1533
CO_2	0.0947	0.1076
H_2	0.1889	0.1893
N_2	0.5128	0.5147
CH_4	0.0151	0.0109
H_2S	0.0003	0.0001
COS	0.0001	0.0001
O_2	0.0074	0.0240
Gasifier perform	nance	
Syngas mass flow (kg/h)	46.83	57.78
Syngas volume flow (Nm ³ /h)	42.90	52.26
Syngas lower heating value (MJ/kg)	4.50	3.98
Specific heat (kJ/kg K)	1.23	1.22
Syngas outlet pressure (MPa)	0.14	0.14
Syngas outlet temperature (°C)	126	275
Maximum reaction temperature (°C)	1034	1000
Cold gas efficiency	96.93%	82.14%
Hot gas efficiency	92.90%	80.96%
Gasifier yield (Nm ³ /kg)	5.36	5.07

Table 3. Effects of air/coal mass ratio.

As shown in table 3, an increase of air flow involves a higher coal consumption and a significant reduction of syngas quality and cold gas efficiency. In these conditions, a higher raw syngas production has been obtained with respect to the "standard" conditions (52.26 Nm³/h, against 42.90 Nm³/h), with a significant decrease of lower heating value (3.98 MJ/kg, against 4.50 MJ/kg in "standard" conditions). Globally, the cold gas efficiency decreases from 96.93% to 82.14%.

As for the main chemical compounds, the expected significant decrease of CO concentration can be noticed, with a corresponding increase of CO_2 concentration. Hydrogen content remains almost constant: as a matter of fact, the effect of a high air injection (and the subsequent reduction of hydrogen content) is completely offset by the significant increasing of steam injection.

3.3. Gasification of high sulphur Sulcis coal

Being the only coal reserve in Italy, Sulcis coal basin plays a very important role from a strategic point of view [48]. Moreover, the closeness between the Sulcis coal mine and the Sotacarbo pilot platform makes the possibility of testing the gasification of Sulcis coal (in mixture with low sulphur coal) particularly interesting¹⁰.

As reported above, a series of experimental tests were carried out by using high sulphur Sulcis coal, and the proximate, ultimate and thermal analyses were previously shown in table 1. In particular, during the last experimental campaign, different runs were carried out by mixing 20% (in weight) of Sulcis coal with South African coal. Due to its volatile content and its high reactivity [49-50], the addition of a small portion of Sulcis coal in the fuel blend involves a significant improvement of the gasification performance. The main results of this kind of test are shown in table 4, in comparison with "standard" operating conditions.

	"Standard"	20% of
	(S.A. coal)	Sulcis coal
Operating paran	neters	
Primary fuel consumption (kg/h)	8.0	10.5
Fuel lower heating value (MJ/kg)	27.18	25.96
Air mass flow (kg/h)	36.8	41.2
Steam mass flow (kg/h)	6.0	7.8
Dry syngas composition	(molar ratios)	
СО	0.1807	0.1772
CO_2	0.0947	0.0969
H_2	0.1889	0.2149
N_2	0.5128	0.4780
CH_4	0.0151	0.0151
H_2S	0.0003	0.0006
COS	0.0001	0.0001
O_2	0.0074	0.0172
Gasifier perform	ance	
Syngas mass flow (kg/h)	46.83	54.84
Syngas volume flow (Nm ³ /h)	42.90	51.49
Syngas lower heating value (MJ/kg)	4.50	4.83
Specific heat (kJ/kg K)	1.23	1.27
Syngas outlet pressure (MPa)	0.14	0.14
Syngas outlet temperature (°C)	126	170
Maximum reaction temperature (°C)	1034	1050
Cold gas efficiency	96.93%	97.20
Hot gas efficiency	92.90%	93.93
Gasifier yield (Nm ³ /kg)	5.36	4.90

Table 4. Gasification performance with 20% of Sulcis coal.

In particular, with respect to the "standard" operating conditions, the experimental tests with 20% of Sulcis coal show a significant increase of coal consumption (10.5 kg/h, higher

 $^{^{10}}$ One of the main goals of the research carried out by Sotacarbo is the relaunch of the industrial activities related with the use of Sulcis coal.

than the maximum value obtained with only South African coal) as a consequence of a small increasing of air flow (41.2 kg/h, with a steam flow of 7.8 kg/h). Syngas production raises up to 51.49 Nm³/h, with a lower heating value of 4.83 MJ/kg (to be compared with 42.90 Nm³/h and 4.50 MJ/kg in the "standard" conditions). Obviously, the sulphur compounds' content increases up to 634.4 ppm (in volume) of H₂S and 126.3 ppm of COS (to be compared with 274.3 and 100.9 ppm, respectively, obtained in the "standard" conditions). Globally, a very high cold gas efficiency (97.20%) has been calculated in these particular operating conditions.

3.4. Gasification with mixtures of CO₂ and O₂

A series of preliminary experimental tests (about 100 hours) were carried out, with South African coal, in order to verify the possibility of operating the gasification process with a mixture of oxygen and carbon dioxide (instead of air) as gasification agent.

In the scientific literature, different studies (mainly based on experimental tests in benchscale plants) report the influence of CO_2 injection in catalytic fluidized-bed biomass gasifiers or pyrolisers [51-52] or in high pressure entrained flow coal gasifiers [53]. In these cases, a CO_2 -rich syngas characterized by a low H₂/CO molar ratio has been obtained by laboratoryscale experimental tests. The results of these studies suggest an assessment of the effect of CO_2 on an autothermal coal gasification process in a fixed-bed low-pressure reactor, as the Sotacarbo pilot gasifier.

Toward this goal, a series of experimental tests were planned in order to investigate the effects of CO_2 injection in the coal gasification process and in the syngas treatment line and some preliminary runs have been already carried out. In particular, during this kind of test, the pilot gasifier was started up according to the conventional procedures; after the reach of the air-blown steady-state, air injection is interrupted and the mixture of oxygen and carbon dioxide is injected into the reactor. These preliminary tests have been conducted significantly far from the "standard" operating conditions, due to the difficulty during this phase of having complete control over the process. In particular, a low oxygen concentration (about 15% in volume) in the oxidant mixture involves a series of problems related to the temperature control (figure 10); as a matter of fact, the low oxygen content reduces the contribution of combustion reactions, and the endothermic gasification reactions are strongly limited. As a consequence, a very low fuel consumption (about 5 kg/h) takes place, with the production of a raw syngas characterized by a very low lower heating value (2.78 MJ/kg) and by a hydrogen content of about 13% (in volume). Globally, cold gas efficiency is very low (59.94%, to be compared with 96.93% in "standard" air-blown conditions).



Figure 10. Typical temperature profiles during CO₂/O₂ gasification tests.

As shown in figure 10, a rise of oxygen concentration (up to 20% in volume) and oxidant mass flow involves an increase of the temperatures in the reactor and, at the same time, the improvement of the syngas quality (the lower heating value rises up to 3.41 MJ/kg, with a hydrogen content of about 18% in volume). On the other hand, a further reduction of the cold gas efficiency (48.53%) takes place. Figure 11 shows the concentrations (in terms of molar fractions) of the main chemical species (CO, CO₂, H₂ and N₂) before and after the injection of the mixture of carbon dioxide and oxygen (with O₂ concentration of 20% in volume); in particular, the last 25 minutes of conventional steady-state air-blown gasification have been reported, together with the transient phase when the oxidant mixture was injected instead of air. During this phase, nitrogen concentration strongly reduces to an average value of about 0.3% (a small nitrogen injection is still used for fuel pressurization during the coal charging phases), whereas carbon dioxide concentration strongly rises up to about 58%. This high CO₂ concentration promotes the Boudouard reaction [54-55]

$$C + CO_2 \Leftrightarrow 2CO \tag{1}$$

and involves an increase of CO concentration in raw syngas; finally, the hydrogen concentration remains almost constant before and after CO_2 injection (except for a short period of instability during the transient phase).



Figure 11. Syngas composition before and after CO₂/O₂ injection.

It is important to note that, due to the preliminary nature of the past experimental tests, the process has not yet been optimized in this particular operating condition. The optimization of the CO_2/O_2 -blown gasification process is one of the main goals for the future experimental campaigns [45].

4. GLOBAL PILOT PLANT PERFORMANCE

A global mass balance of the Sotacarbo pilot plant has been carried out in order to evaluate the overall plant performance and both hydrogen and carbon balances. The results reported here come from a detailed analysis made up on the basis of the experimental data collected for every plant section. Through the processing of these data, a global mass balance of the plant has been assessed and, for every section, the performance and properties of each flow have been determined with good accuracy.

This evaluation considers a hypothetical commercial near zero emissions configuration, which includes the gasification section and the CO_2 -free hydrogen production line. Therefore, the balance has been carried out, on the basis of the experimental data, with the theoretical hypothesis that all syngas from the depulverization system¹¹ is heated, compressed and sent to the hot gas treatment line.

4.1. Global plant performance in "standard" gasification condition

Figure 12 and table 5 show the main results of this evaluation, with reference to the above described "standard" steady-state gasification of low sulphur South African coal.

In particular, figure 12 shows a simplified scheme of the Sotacarbo pilot plant with the main results of a global balance of the whole of the experimental equipment, mainly expressed in terms of hydrogen and carbon content. For every stream, mass flow (m, in

¹¹ It includes wet scrubber, first cold gas desulphurization (CGD) stage and ESP.

kilograms per hour) and lower heating value (LHV, in megajoule per kilogram) have been reported, together with the molar flows (in moles per hour) of equivalent hydrogen (H_{eq}), of effective molecular hydrogen (F_{H2}), of atomic carbon (C_{eq}) and of molecular CO₂ (F_{CO2}). In particular, the molar flow of equivalent hydrogen is the global amount of hydrogen contained in the chemical species which can potentially contribute to the overall hydrogen production:

$$H_{eq} = F_{H_2} + \frac{F_{CH_4}}{2} + F_{H_2S} + F_{H_2O}$$
(15)

where F_i is the molar flows of each chemical species (hydrogen, methane, hydrogen sulphide and steam, respectively). According to this definition, the global balance of H₂ is influenced by the steam injection and condensation, by the hydrogen content in coal, and, slightly, by the air moisture.

In parallel, the molar flow of atomic carbon represents the global amount of carbon contained in the chemical species which could contribute to CO_2 production when syngas is burned:

$$C_{eq} = F_{CO} + F_{CO_2} + F_{CH_4} + F_{COS}$$
(16)

The global balance of the gasification section is directly evaluated by the experimental data; this justifies the apparent incongruence in the hydrogen and carbon balances. As a matter of fact, the reported data for coal, gasification agents and produced syngas are averaged in a time window in which the process can be considered in steady-state. On the contrary, it is currently impossible to evaluate the direct effects of the gasification process on the ash composition, being that the discharge temporization time is comparable with the duration of the considered time window. Therefore, ash composition is significantly conditioned by a series of phenomena which take place before the reach of steady-state phase.

Table 5 shows, stream by stream, the mass and volume flows, pressure, temperature, lower heating value (LHV) and specific heat, together with the gaseous streams composition, in terms of molar fractions.

In both figure 12 and table 5, raw syngas composition (stream 4) is expressed in dry basis, the data directly provided by the gas chromatograph. Downwards of the wet scrubber, syngas is saturated by water injection; therefore, in the reported data, the moisture content has been considered.



Figure 12. Synthesis of the global plant balance.

4.2. Global hydrogen balance

As for the gasification section, the material balance in "standard" conditions show that hydrogen production is mainly influenced by steam injection (52%) and secondarily by the hydrogen content in coal (43%, considering the primary fuel with its humidity), whereas the contribution of air moisture (5%) is very low. Obviously, this distribution is strongly conditioned by the gasification parameters and a variation of these percentages can be expected for different operating conditions.

Hydrogen content remains almost constant through syngas cleaning processes (washing section and hot gas desulphurization processes), while it significantly changes through the water-gas shift section, in which CO reacts with steam and H_2 content is strongly increased. In particular, the experimental results in this section show that the process operates very close to the chemical equilibrium: CO conversion in the first stage is about 90%, whereas in the second stage a conversion of about 85% takes place. Globally, a final CO concentration lower than 2% (in volume) can be achieved by the double-stage process.

Globally, the gasification of 8.0 kg/h of low sulphur South African coal allows for production of about 2.3 kg/h of hydrogen. About 1.86 Nm³ of hydrogen can be produced for every kilogram of South African coal or, in other words, for every kilowatt of gasified coal a production of 0.70 kW of hydrogen can be obtained. In general, based on results from some preliminary tests, a slight decrease of hydrogen production can be expected when only high sulphur Sulcis coal is gasified, due to the different operating conditions of the gasification process.

Even if hydrogen purity (94-97%) is significantly lower with respect to the typical values (99.999%) that can be obtained with the modern PSA systems [10, 56], these values are fully acceptable considering that, in the pilot plant, produced hydrogen is only used to enrich clean syngas which feeds the internal combustion engine

	1	2	3	4	5	6
	Coal	Air	Steam	Raw gas*	Syngas	Syngas
Mass flow (kg/h)	8.00	36.80	3.70	46.83	48.54	48.09
Volume flow (Nm ³ /h)	-	28.68	4.60	42.90	46.21	45.89
Pressure (MPa)	0.14	0.14	0.14	0.14	0.13	0.14
Temperature (°C)	25	25	110	126	50	350
LHV (MJ/kg)	27.18	0.00	0.00	4.50	4.34	4.38
Specific heat (kJ/kg K)	-	1.014	1.67	1.233	1.276	1.280
	Stree	um compositi	on (molar fra	action)		
CO	-	-	-	0.1807	0.1677	0.1678
CO_2	-	-	-	0.0947	0.0703	0.0703
H ₂	-	-	-	0.1889	0.1753	0.1753
N ₂	-	0.7742	-	0.5128	0.4760	0.4760
CH ₄	-	-	-	0.0151	0.0140	0.0140
H_2S	-	-	-	0.0003	0.0000	0.0000
COS	-	-	-	0.0001	0.0001	0.0000
O ₂	-	0.2076	-	0.0074	0.0069	0.0069
H ₂ O	-	0.0182	1.0000	-	0.0897	0.0897
	7	8	9	10	11	12
	HT	LT steam	Syngas	Syngas	Hydrogen	Off-gas
	steam					
Mass flow (kg/h)	7.29	2.08	57.46	31.82	2.30	29.05
Volume flow (Nm ³ /h)	9.08	2.59	57.56	40.26	14.85	24.84
Pressure (MPa)	0.24	0.24	0.13	0.13	0.13	0.13
Temperature (°C)	350	250	250	30	45	45
LHV (MJ/kg)	-	-	3.44	6.21	66.38	1.55
Specific heat (kJ/kg K)	1.674	1.674	1.388	1.672	8.602	0.124
	Stree	um compositi	on (molar fra	action)		
CO	-	-	0.0134	0.0191	0.0104	0.0247
CO_2	-	-	0.1767	0.0025	0.0007	0.0037
H ₂	-	-	0.2605	0.3715	0.9444	0.0419
N_2	-	-	0.3801	0.5420	0.0444	0.8479
CH ₄	-	-	0.0012	0.0160	0.0000	0.0257
H_2S	-	-	0.0000	0.0000	0.0000	0.0000
COS	-	-	0.0000	0.0000	0.0000	0.0000
O ₂	-	-	0.0055	0.0078	0.0000	0.0126
H ₂ O	1.0000	1.0000	0.1526	0.0411	0.0000	0.0434
* Dry basis						

Table 5. Stream properties and composition.

Considering the whole process, as shown in figure 13, about 58% of produced syngas comes from steam injected into the water-gas shift section, while 22% comes from the gasification steam, 18% comes from coal and only 2% comes from the gasification air (considered with its humidity).



Figure 13. Global hydrogen balance.

4.3. Global carbon balance

Hypothetically, the combustion of 8.0 kg/h of South African coal (characterized by a total carbon content of 75.56%, as shown in table 1) involves the production of about 22 kg/h of CO_2 . Through the gasification process, carbon reacts with gasification agents and it is converted in a mixture of CO, CO_2 , CH_4 and a small amount of COS, whereas a portion (currently about 8-10% of total carbon amount in coal¹², as results from the experimental tests) remains unreacted in the bottom ash.

Carbon content in raw syngas remains almost constant through the wet scrubber and electrostatic precipitator (carbon amount removed as tar can be neglected), whereas a little variation takes place in the first cold gas desulphurization stage. In particular, during the experimental tests with low sulphur coal, a pH value of about 9.5-10.0 was used for the desulphurization solvent (an aqueous solution of sodium hydroxide), with a subsequent absorption of about 20% of CO_2 .

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

As mentioned, carbon dioxide absorption takes place in a bubbling reactor which operates at about 30 °C through different amine-based solvents; in particular, in this analysis a 5M monoethanolamine (MEA) solution was considered, according to the plant design conditions. In this way, the process (which has been significantly improved during the recent experimental campaign) operates with a global efficiency of about 99%. The remaining carbon content in syngas is separated through PSA and can be found in off-gas, which is sent to the flare, except for a small amount which remains in hydrogen-rich stream.

Globally, the gasification of 8.0 kg/h of South African coal, with the hypothesis that all syngas should be sent to the hydrogen production line, involves the emission of about 2 kg/h of CO_2 , with a global removal efficiency of about 90%. In other words, as shown in figure 14, being 100 the atomic carbon which enters in the overall process through coal, about 8-10% is removed through the bottom ash, 6% is separated in the first cold gas desulphurization stage and 75% is separated as CO_2 in the carbon dioxide absorber, while the remaining 10-11% can be found in the process products (hydrogen-rich gas and off-gas).

¹² This high value is not referred to the "standard" operating conditions, but it is the typical value measured during the last experimental campaign. As specified later, the reduction of the unburnt content is one of the main goal of the future gasification tests.



Figure 14. Global carbon balance.

4.4. Pollutant emissions

As for pollutant emissions, the wet scrubber allows for fine dust and tar removal, in particular for South African coal. When Sulcis coal is used, tar content in raw syngas becomes very high, even when the syngas outlet temperature is higher with respect to the gasification of South African coal; in this case, depending on the percentage of Sulcis coal in the fuel blend, the wet scrubber could be unable to assure an adequate removal. Even in this case, fine tar removal can be achieved by using the electrostatic precipitator.

The hot gas desulphurization system typically operates at about 350-400 °C by using commercial zinc oxides-based sorbents. It should be able to assure an efficient H_2S separation even when high sulphur coal is used, but, in order to protect the ESP from an acid atmosphere, in general it operates together with the first cold gas desulphurization (CGD) stage. As mentioned above, the latter allows a first significant reduction of sulphur compounds operating the absorption of H_2S in a metallic packed column, in which syngas can be washed by an aqueous solution of sodium hydroxide.

Otherwise hot gas desulphurization, it is possible to treat syngas in the second sulphur compounds absorber stage. Both these units (first and second cold gas desulphurization systems) operate a separation of hydrogen sulphide (its efficiency strongly depends on the pH of the solvent solution), but the COS concentration remains about constant.

Both cold and hot gas desulphurization systems (considered independently of each other) allow for obtainment of a final H_2S concentration lower than 10 ppm (in volume), compatible with the use of clean syngas to feed the internal combustion engine. In many cases, downwards of the hot gas desulphurization system, a final H_2S and COS concentration lower than 1 ppm has been measured, even using high sulphur coal. This concentration is generally compatible with some technologies for distributed power generation, like internal combustion engines, micro gas turbines and different kinds of fuel cells [57-59].

5. FUTURE DEVELOPMENTS OF THE GASIFICATION PROCESS

The performance of the gasification process was significantly improved during the last experimental campaign; in particular, as reported above, the best operating conditions have been defined for the gasification of South African coal, assumed as the reference fuel.

The interest in optimizing the technology for different commercial applications involves the need to further improve the performance of the process with the reference fuel (in particular reducing the carbon content in the bottom ash) and to assure a great flexibility in terms of primary fuel, oxidant agents and so on.

5.1. Coal gasification tests

As for the optimization of the coal gasification process, the effects of fuel granulometry and reactivity needs to be systematically analyzed. Currently, coal gasification tests have been carried out using a constant coal granulometry (between 5 and 10 mm), obtained through a crushing of the raw fuel and its riddling, with the separation of fines and powders. A reduction of coal granulometry could involves an increase of reaction rate¹³, a subsequent rise of fuel load and syngas production, the reduction of the eventual formation of preferential paths into the fuel bed and a more efficient fuel utilization with a lower carbon content in the bottom ash¹⁴ [60-62]. On the other hand, a rise in pressure drops can be expected with the subsequent need to increase the injection pressure of the gasification agents. The goal of the planned experimental tests is to define the minimum fuel granulometry compatible with the operation of the grate and the pressure profile in the reactor.

The pilot gasifier has been recently equipped with a system for sampling and the characterization of tar; after the setting of this system, a more detailed characterization of produced syngas and of the tar separation system will be assessed in order to analyze the effects of the operating conditions (in particular fuel composition and thermal profiles) on tar formation and properties.

Some experimental tests will also be carried out in order to evaluate the performance of the gasifier with air enriched in oxygen [63-64] and to optimize the gasification with mixtures of oxygen and carbon dioxide as oxidant agent.

In particular, as for air enrichment, preliminary tests show that the gasification process can be operated with an oxygen concentration in the oxidant agent up to 40% (in volume); oxygen concentration in the gasification air has been gradually increased, thus slightly reducing the actual oxygen/coal mass ratio; as a matter of fact, the reduction of nitrogen dilution requires a low heat provided by the combustion reactions. As a consequence, an increase of the hydrogen concentration (up to the average value of about 50%, with picks of 55-56%) has been obtained in raw syngas, with a carbon monoxide concentration between 20 and 25% and a reduction of CO_2 concentration (5-12%). It is important to notice that these results are preliminary, and the process needs to be optimized.

5.2. Biomass or coal/biomass gasification tests

¹³ This is mainly due to the increasing of the contact surface between solid fuel particles and gaseous gasification agents (air and steam).

¹⁴ According with the unreacted-core shrinking model, presented by Wen in 1968 [60], the process is characterized by three resistances: external film diffusion, diffusion through the ash layer and the reaction at the surface of the unreacted core. In large coal particles, the formation of an ash layer gradually reduces the reaction rate, those generating an inert ash layer, an unreacted core and as a consequence, a high global carbon content in the discharged ash.

Biomass is an abundant carbon-neutral source of renewable energy, and gasification provides a competitive way to convert biomass to syngas containing hydrogen, carbon monoxide, methane and carbon dioxide [19]. Syngas, obtained from biomass gasification, can be used to generate heat and power like natural gas [65-66], to synthesize other chemicals and liquid fuels [67-68] or to produce hydrogen [69-71]. Significant advances have been made in the technology of biomass gasification and syngas utilization [19]; however, more research is needed to improve syngas quality for its commercial uses.

In the co-gasification process, with the blending of biomass and coal, it is possible to obtain a syngas which has great flexibility to be used in several ways. Co-gasification of biomass with coal can be considered as a bridge between the energy production systems based on fossil fuels and those based on renewable energy sources. The high reactivity of biomass and its highly volatile content suggest that some synergetic effects might occur in simultaneous thermochemical treatment of coal and biomass, depending on the gasification conditions [72].

To this aim, a series of gasification tests have been planned in order to evaluate the performance of the gasification process feed with wood-based biomass, mixtures of biomass and coal [73] and, eventually, waste [74-75]. The effect of the main variables, such as temperature profile, feedstock composition and air/fuel mass ratio, will be studied on gas composition, lower heating value, cold gas efficiency, gasifier yield and tar content.

Preliminary tests of co-gasification of wood-based biomass and coal (with air as gasification agent), have been carried out in the pilot up-draft fixed-bed gasifier. The effect of the feedstock composition with a varying content of wood-based biomass on the co-gasification behaviour has been preliminarily studied.

In particular, table 7 shows a comparison between the "standard" operating conditions and the main results of a gasification test in which 20% (in weight) of wood-based biomass (the same wood pellet generally used as start-up fuel, and for which the characterization is shown in table 6) has been mixed with South African coal. It is important to underline that these co-gasification conditions come from a preliminary test, and the process has not been optimized yet.

In order to compare the results and extrapolate the effect of the addition of biomass in the feeding fuel, the considered co-gasification tests have been carried out with the same operating conditions assumed as "standard" (except for primary fuel composition): air injection of 35-37 kg/h, steam injection of 6-7 kg/h and maximum temperature between 1000 and 1050 °C.

As expected, biomass being more reactive than South African coal [76-78], its introduction involves, with respect to "standard" operating conditions, an increase of fuel consumption (from 8.0 to 10.2 kg/h) and a subsequent rise of syngas production (from 43 to $45 \text{ Nm}^3/\text{h}$).

Table 6. Wood pellet characterization.

	100%	20% wood p.
	wood pellets	80% S.A. coal
Proximate an	1alysis (% in weigh	et)
Fixed carbon	17.70 %	61.60 %
Moisture	8.57 %	4.63 %
Volatiles	73.32 %	21.71 %
Ash	0.42 %	12.06 %
Ultimate an	alysis (% in weight	•)
Total carbon	79.51 %	76.35 %
Hydrogen	11.18 %	5.32 %
Nitrogen	0.32 %	1.18 %
Sulphur	0.00~%	0.46 %
Moisture	8.57 %	4.63 %
Ash	0.42 %	12.06 %
Thermal	analysis (MJ/kg)	
Higher heating value	18.45	26.17
Lower heating value	16.85	25.11

Table 7. Gasification performance with 20% of wood pellets.

	"Standard"	Co-gasific.
Operating param	neters	
Primary fuel consumption (kg/h)	8.0	10.2
Air mass flow (kg/h)	36.8	35.0
Steam mass flow (kg/h)	6.0	6.7
Dry syngas composition	(molar ratios)	
СО	0.1807	0.1681
CO_2	0.0947	0.0883
H_2	0.1889	0.1888
N_2	0.5128	0.5046
CH_4	0.0151	0.0173
H_2S	0.0003	0.0000
COS	0.0001	0.0001
O_2	0.0074	0.0328
Gasifier performance		
Syngas mass flow (kg/h)	46.83	49.23
Syngas volume flow (Nm ³ /h)	42.90	45.14
Syngas lower heating value (MJ/kg)	4.50	4.44
Specific heat (kJ/kg K)	1.23	1.23
Syngas outlet pressure (MPa)	0.14	0.14
Syngas outlet temperature (°C)	126	142
Maximum reaction temperature (°C)	1034	1047
Cold gas efficiency	96.93%	85.30%
Hot gas efficiency	92.90%	82.47%
Gasifier yield (Nm ³ /kg)	5.36	4.43

Syngas composition and properties remain almost constant¹⁵, particularly hydrogen concentration (about 18-19%) and lower heating value (4.5 MJ/kg), while the cold gas efficiency strongly decreases.

5.3. Preliminary tests on biochar production

Biomass is a very versatile renewable energy resource which can also be used to produce CHP (combined heat and power) and both biochar and bio-oil, each of which has potential economic value for various uses. In particular, soil application of biochar may enhance both soil quality and can be an effective means of sequestering large amounts of carbon, thereby helping to mitigate global climate change through carbon sequestration [79-81] and enhanced plant growth, which will also enhance the sustainability of biomass as a renewable energy resource. Moreover, biochar is highly absorbent and therefore increases the soil's ability to retain water, nutrients and agricultural chemicals, preventing water contamination and soil erosion. Another potential use for biochar is metal adsorption [82].

Biochar can be produced by pyrolysis or gasification systems. To this aim, the possibility of carrying out a series of gasification and biochar demonstration and characterization runs, in order to optimize the biochar production in the pilot up-draft fixed-bed gasifier, is currently under evaluation in strict cooperation with Hamilton Maurer International, Inc. (Texas, United States).

In particular, after about six hours of steady-state biomass gasification, the run will be stopped using a nitrogen purge to "freeze" the gasifier fuel-bed for biochar recovery and characterization. In order to optimize the biochar production and recovery as a co-product, the characterization of the biochar within the gasifier can be important as a function of the bed level. For all the demonstration and characterization runs, both the biomass feedstock and biochar as a function of bed depth will be characterized: proximate and ultimate analysis, heat of combustion, surface area and XRF (X-ray fluorescence) mineral analysis will be done in Sotacarbo Laboratories. Biochar will also be characterized by the University of Florida both in the laboratory and applied to different soils to characterize the impact of biochar on plant growth and soils absorption of plant nutrients.

6. FUTURE DEVELOPMENTS OF THE SYNGAS TREATMENT PROCESSES

The flexibility of plant configuration will allow a long series of experimental tests in order to optimize each syngas treatment process in different operating conditions and to assess the performance of the whole plant on the basis of different specific applications.

In particular, a series of experimental tests has been planned in order to evaluate the performance of the hot gas desulphurization process by varying the operating conditions (temperature and sorbent composition), to optimize the water-gas shift process with different catalysts (and with different steam/CO molar ratios) and to evaluate the effects of solvent composition and operating parameters on H_2S and CO_2 cold gas absorption processes.

¹⁵ Except for oxygen concentration in raw syngas, which is still high (being that the process is not optimized) in the syngas from co-gasification tests.

Moreover, a series of bench-scale tests are currently in planning in order to preliminarily evaluate the possibility of applying the coal-to-liquids (CtL) technology in the Sulcis coal basin.

6.1. Hot syngas desulphurization process

In order to support the hot gas desulphurization experimental tests in the pilot platform, a bench-scale plant (called MOSCA, Metal Oxides for Sulphur Compounds Adsorption) has been developed and tested with three different commercial zinc oxides-based sorbents and in different operating conditions [83].

The plant was conceived to reproduce the operative conditions of the hot gas desulphurisation process in the Sotacarbo pilot plant. It consists of a feed gas apparatus, a fixed-bed desulphurisation reactor, a washing bottle for the off-gas cleanup and a gas sampling and analysis equipment.

A bi-component mixture of H_2S and N_2 (with a hydrogen sulphide concentration of 1.5% in volume) has been selected in order to reproduce the typical H_2S concentration in a coal syngas obtained through the gasification of Sulcis coal in an air-blown fixed-bed gasifier. In this way the operating conditions of the Sotacarbo pilot plant have been obtained as for H_2S concentration.

Gas stream depuration takes places in a quartz fixed-bed reactor (figure 14), characterized by an internal diameter of 50 mm and filled with a known volume of sorbent. A fixed quartz grate and an inert disc made of ceramic fiber (completely inert for H_2S adsorption, as experimentally verified) allow the stability of the sorbent bed. A quiet zone has been located upwards of the sorbent bed in order to assure a uniform distribution of the gaseous flow and to allow its heating.



Figure 15. The MOSCA reactor.

The reactor is placed horizontally in a tubular furnace in which a constant temperature can be maintained by a PID (proportional-integral-derivate) controller. The experimental system operates in an open circuit with a constant pressure of about 0.14 MPa. Downstream of the reactor, treated gas is sent to a washing bottle, in which it bubbles into an aqueous 5 M NaOH solution, which allows the chemical absorption of the remaining traces of hydrogen sulphide.

Until now, the experimental tests only allowed for the sorbent characterization during H_2S adsorption on the bi-component mixture, in order to focus the attention on the reaction between hydrogen sulphide and zinc oxide. A series of sulphidation/regeneration cycles is currently in progress in order to evaluate the behaviour of the process in its whole development and the effects of oxygen¹⁶ or steam in the regeneration phase [84]. These tests should give the information needed to predict the performance and to design the regeneration system for the pilot plant.

Moreover, a series of experimental tests has been planned in order to verify the effects of steam and of a reducing ambient [85-86] on the sulphidation process; to this goal, the experimental apparatus will soon be equipped with a gas mixer and a peristaltic pump in order to create a gas mixture as similar as possible to the coal syngas.

At the moment, a thermogravimetric study is in progress in order to evaluate the amount of sulphur released by the sorbents during the regeneration process. In this way, interesting indications of the kinetic behaviour of the process will be obtained [87]. The thermogravimetric analysis is operated on the spherical particles and, in parallel, on the powdered sorbent, in order to separate the effects of diffusion on the overall kinetic.

6.2. Optimization of CO₂ absorption process

Before the optimization of the pilot CO_2 capture system, a set-up of the double-stage water-gas shift process is need in order to stabilize the syngas output properties and to verify the effects of operating temperature [88] and steam/CO molar ratio [88-89] in both high and low temperature stages. Moreover, a series of experimental tests will be carried out in order to test the process with conventional catalysts [90-91] instead of non pyrophoric platinum-based catalysts.

As for CO_2 absorption, a series of tests has been planned in order to evaluate the effect of the main operating parameters (such as temperature, CO_2 partial pressure, CO_2 loading, gas flow rate and solvent composition) on the performance of the carbon dioxide capture system.

The temperature influences the chemical and physical equilibrium of the process, along with all the chemical-physical parameters such as viscosity, density and so on [92]. Therefore, the need to evaluate the effects of a temperature variation on the absorption system suggests carrying out a series of experimental tests with different operating temperatures¹⁷.

 CO_2 partial pressure can be indirectly modified by varying steam injection in the watergas shift process or through a direct carbon dioxide injection upwards of the carbon capture section. This parameter influences mass transfer and CO_2 reaction into the liquid phase, but only a little variation of global removal efficiency is expected [93].

An increase of gas flow rate (which can be controlled through the compressor that sends syngas to the hydrogen production line, as shown in figure 5) involves a rise of the effective interfacial area between liquid and gas phases; therefore a raise in the whole absorption efficiency, up to a maximum value, can be expected.

¹⁶ Currently, regeneration process is carried out by using oxygen (3% in volume) diluted in nitrogen, provided in bottles; a gas mixture will be soon introduced in order to test the process with different oxygen concentrations.

¹⁷ These tests require some simple modifications to the plant equipment, in order to allow a rigorous control of the operating temperature.

With a relatively simple plant modification, it will also be possible to test the CO_2 absorption system at different pressures. As a matter of fact, with the operating pressure of PSA 0.3 MPa, it is possible to compress syngas before the second CO_2 absorption reactor, using the same compressor for both processes.

The choice of the absorption solvents can be determined by a number of factors, such as absorption efficiency, energy consumption, corrosion and solvent degradation. Most of the experimental tests have been made, in the Sotacarbo pilot plant, using MEA in different concentrations due to their high reactivity and low cost [94-95]. Obviously, solvent concentration influences the process up to a maximum value, depending to the kind of reactor [93, 96]. The increasing MEA concentration implies a higher amount of active solvent available to react with carbon dioxide; moreover, this increase involves a rise of solvent viscosity, which effects will be evaluated in the experimental tests.

Moreover, there is a growing interest in using mixed amine solvents: these solutions often provide greater absorption performance or meet unique needs when compared to the solutions of single alkanolamines [97-101]. To this aim, the possibility of carrying out a series of experimental tests, in the Sotacarbo pilot plant, with different solvent blends, with particular reference to an aqueous solution of piperazine (PZ) activated MDEA solution appears interesting. As a matter of fact, the regeneration of MEA-based solvents involves a heat request significantly higher than those needed for the regeneration of MDEA, which has a higher maximum loading capacity and is is less corrosive than MEA [102-104]. However MDEA, being a tertiary amine, does not react with CO_2 directly and it is necessary to use a promoter which can enhance the reaction rate without diminishing the MDEA advantages. Piperazine has been shown to be an effective promoter due to its rapid formation of carbamates with CO_2 [105-107]. During the preliminary tests, PZ concentration in the activated aqueous MDEA solution was 2% (in weight) while the total amine concentration in the solution was 30% in weight. When CO₂ is absorbed into an aqueous mixed amine solution of MDEA (RRCH₃N, where R represents CH₂-CH₂OH) and PZ, the following reaction may take place in the liquid phase [108]:

$CO_2 + RRCH_3N + H_2O \Leftrightarrow RRCH_3NH^+ + HCO$	V_3^- (reaction CO ₂ /MDEA)	(17)
$CO_2 + PZ + H_2O \Leftrightarrow PZCOO^- + H_3O^+$	(formation of monocarbamate)	(18)
$CO_2 + PZCOO^- + H_2O \Leftrightarrow PZ(COO^-)_2 + H_3O^+$	(formation of dicarbamate)	(19)
$CO_2 + RRCH_3N + PZ \Leftrightarrow RRCH_3NH^+ + PZCOC$	<i>Q</i> ⁻ (form. of monocarbamate by PZ/MDEA)	(20)
$CO_2 + RRCH_3N + PZCOO^- \Leftrightarrow RRCH_3NH^+ + R$	PZ(COO ⁻) ₂ (formation of dicarbamate by PZCOO ⁻ /MDEA)	(21)
$CO_2 + OH^- \Leftrightarrow HCO_3^-$	(formation of bicarbonate)	(22)
$HCO_3^- + H_2O \Leftrightarrow CO_3^{2-} + H_3O^+$	(dissociation of bicarbonate)	(23)
$PZ + H_3O^+ \iff PZH^+ + H_2O$	(protonation of PZ)	(24)
$PZCOO^{-} + H_3O^{+} \Leftrightarrow PZH^{+}COO^{-} + H_2O$	(protonation of monocarbamate)	(25)

$RRCH_{3}N + H_{3}O^{+} \Leftrightarrow RRCH_{3}NH^{+} + H_{2}O$	(protonation of MDEA)	(26)
$2H_2O \Leftrightarrow OH^- + H_3O^+$	(ionization of water)	(27)

According to the preliminary results, MDEA/PZ solutions appear to be attractive new blended solvents for CO_2 removal. By varying the relative concentrations of the amines, an optimum absorption system can be obtained for the specific application.

The design of a solvent regeneration system is currently under development. The introduction of this system will allow for the possibility to test the integrated absorption and regeneration process and to strongly reduce the operating costs of the experimental tests. This system will be optimized for the regeneration of MEA-based solvents but, due to its flexibility, it will allow operation with different solvent solutions.

In order to reduce the experimental tests in the pilot carbon capture unit, the above mentioned evaluations will be supported through a series of experimental tests which will be carried out in a bench-scale CO_2 absorption unit (called GAIA, greenhouse-gas absorption in amine-based solvents), which has been recently installed (in cooperation with the Department of Chemical Engineering of the University of Cagliari) in the Sotacarbo laboratories (figure 16). This unit includes a glass packed column characterized by an internal diameter of 80 mm and a bed height of 1000 mm. The reactor is randomly filled with Rashig rings (with a diameter of about 8 mm) made of glass. Syngas is simulated through a flow of CO_2 diluted in nitrogen (both these gases are supplied in bottles) and solvent (up to 225 Ndm³/h, with a pressure up to 1.0 MPa) is sent to the reactor through a proper pump. The bench-scale plant includes a regeneration section in which exhaust solvent is heated with a steam flow and releases captured CO_2 . The whole system is equipped with different pressure and temperature probes, and gas composition is analyzed through the same gas chromatograph used in the pilot platform.



Figure 16. The GAIA bench-scale CO₂ absorption column.

6.3. Coal-to-liquids experimental tests

Besides hydrogen and electrical energy, coal syngas can be used for the production of a series of chemical products such as substitute natural gas, methanol (MeOH, CH₃OH), dimethylether (DME, CH₃OCH₃), ammonia, gasoline and so on. This kind of production could involve a series of potential benefits such as the reducing of dependence of oil and natural gas import, low pollutant emissions, a high feedstock flexibility and high efficiency of poligeneration processes [109-111].

The technologies for chemical synthesis of liquid fuels from coal syngas are well known and established, but the increasing interest in this kind of process needs a scientific and technical effort in order to optimize the plant configuration and reduce the production costs [112].

In this field, Sotacarbo is starting a study for the optimization of a coal-to-liquids (CtL) process for the production of methanol, DME and (in a second phase) Fisher-Tropsch (FT) liquids from high sulphur Sulcis coal.

In general, methanol synthesis from coal syngas takes place according to a well known mechanism which can be described through the two following reactions [21]:

$$CO + 2H_2 \Leftrightarrow CH_3OH$$
 (28)

$$CO_2 + 3H_2 \Leftrightarrow CH_3OH + H_2O$$
 (29)

Both these reactions, being exothermic¹⁸ and taking place with reduction of volume, are promoted by low temperature¹⁹ and high pressure. They historically took place in gas-phase fixed-bed reactors filled with copper catalysts, which mainly promote reaction 28. Therefore, a stoichiometric number (SN) is defined as:

$$SN = \frac{x_{H_2} - x_{CO_2}}{x_{CO} + x_{CO_2}}$$
(30)

where x_i represents the molar fraction of species. The best conversion efficiency can be achieved when SN is about 2.02-2.04 [21], with a CO₂ concentration of about 2.5-3.5% (in volume) [113].

Recently the performance of methanol synthesis from coal syngas has been significantly improved through the development of liquid-phase slurry bubble column reactors²⁰ (SBCR). In these processes, solid copper (Cu/ZnO/Al₂O₃) catalysts [114-117] are in powder form and it is slurried in an inert mineral oil, which operates as a temperature moderator and a heat removal medium, transferring the heat of reaction from the catalyst surface via the liquid slurry to boiling water in an internal tubular heat exchanger [111, 118].

As for dimethylether synthesis, among the methanol synthesis reactions, a further reaction (dehydration of methanol) takes place in the meantime and in the same reactor [119]:

$$2CH_3OH \Leftrightarrow CH_3OCH_3 + H_2O \qquad (dehydration of methanol) \tag{31}$$

This reaction is promoted by the same catalysts used for methanol synthesis with the addition of some solid-acid catalysts (such as ferrierite, γ -alumina, tungsten-zirconia and sulphated-zirconia) [120-123].

In this context, the first step of the Sotacarbo research involves the development of a flexible bench-scale slurry bubble column reactor for methanol and DME synthesis from coal syngas, which will be simulated through a gas mixer. The data collected during the experimental tests could allow (in a second phase of the project) the design of a small scale pilot unit²¹ in which the whole syngas production and treatment processes could be tested and optimized.

¹⁸ The reactions 26 and 27, strongly exothermic, involve the production of 90.84 and 49.57 kJ/mol, respectively.

¹⁹ Methanol synthesis processes take place at about 250-270 °C. As a matter of fact, low temperature shifts the equilibrium of the reaction to the products, but the minimum operating value is defined by the activation of catalysts.

²⁰ This liquid phase process has been initially developed in United States since 1981 by Air Products and Chemicals, Inc., and called LPMeOHTM (Liquid Phase Methanol).

²¹ Due to the properties of the Sotacarbo pilot platform (air-blown gasification process, atmospheric pressures and so on), the CtL pilot unit will be totally independent from the current plant, except for some auxiliaries equipments.

7. CONCLUSION

At present, the 700 hours of experimental tests carried out in the Sotacarbo coal-tohydrogen pilot plant allowed for optimization of the gasification process fed with South African coal, evaluation of the global effects of the main operating parameters and, in general, definition of the performance, in design conditions, of every syngas treatment section.

As obtained by the experimental tests, the best gasification performance with a low sulphur South African coal takes place with an air flow of about 37 kg/h and a steam flow of about 6 kg/h. As a consequence of these operating conditions, fuel consumption amounts to 8 kg/h, and produced syngas (about 43 Nm^3 /h) is characterized by a lower heating value of 4.5 MJ/kg, with a hydrogen content of about 19% (in volume).

The gasification cold gas efficiency (which is strongly influenced by the operating parameters) has been considered as the main performance indicator for the comparison of different operating conditions, representing the ratio between the chemical power associated to produced syngas with respect to those associated to the primary fuel. In "standard" operation, it amounts to 96.93%. In general, as expected, the experimental results show that an increase of air injections leads to a rise of coal consumption and syngas production, but, on the other hand, a significant decrease of syngas lower heating value and of the cold gas efficiency takes place.

In general, a slight increase of the fuel reactivity (corresponding to the use of a small percentage of a more reactive fuel, such as Sulcis coal or biomass) involves a significant rise in coal consumption and syngas production. In particular, the additon of 20% of Sulcis coal in the fuel blend involves an increase of syngas production (about 20%, from 42.90 to 51.49 Nm³/h) and a rise in cold gas efficiency (from 96.93% in "standard" condition to 97.20% with Sulcis coal). On the other hand, the addition of 20% of wood pellets still involves a slight increase in syngas production (5%, from 42.90 to 45.14 Nm³/h), but in the meantime a significant reduction of cold gas efficiency (from 96.93% to 85.30%) takes place; this is mainly due to the preliminary nature of the tests, with the process not optimized yet.

As for the whole coal-to-hydrogen process, with the theoretical hypothesis that all produced syngas is treated in the CO_2 -free hydrogen production line, the potential specific hydrogen production is about 1.86 Nm³ per kilogram of coal. Obviously, in the Sotacarbo pilot plant, hydrogen production has not been optimized, due to the experimental aim of the plant. This justifies the relatively high energy content in the off-gas, which is currently sent to the flare. With a view towards the application of this technology to an industrial coal-to-hydrogen plant, it is possible both to maximize hydrogen production (thus reducing energy content in the offgas) or to reduce hydrogen production itself and use the rich off-gas for the co-production of electrical energy.

Global carbon dioxide emissions can be strongly reduced (up to about 90%) through a one-stage CO_2 capture plant, which is currently characterized by an absorption efficiency of about 99% by using a MEA solution as solvent. The global CO_2 emission can be further reduced by using a two-stage capture system, with a first intermediate absorption stage between high and low temperature water-gas 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 separation and storage of

more than 90-95% of the global carbon content, with some economical advantages related with the Emissions Trading System.

As for pollutant emissions, the integration of a wet scrubber and electrostatic precipitator allows for obtainment of a negligible dust emission, whereas tar content is strongly reduced, even when Sulcis coal is gasified. The hot gas desulphurization process allows for obtainment of a final H₂S concentration lower than 10 ppm (in volume, even with high sulphur Sulcis coal) and, in many cases, lower than 1 ppm.

The studies and experimentations carried out on the Sotacarbo pilot platform represent only the first phase of a large series of experimental campaigns (by using the pilot platform with the support of the Sotacarbo Laboratories) which are in progress or in planning in order to optimize the gasification process and syngas treatment line for different applications in the field of distributed power generation through the use of hydrogen as energy carrier.

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9. NOMENCLATURE

<u>Symbols</u>	
C_{eq}	molar flow of atomic carbon (mol/h)
F_i	molar flow of species i (mol/h)
H_{eq}	molar flow of equivalent hydrogen (mol/h)
LHV_G	raw syngas lower heating value (MJ/kg)
LHV_C	coal lower heating value (MJ/kg)
т	stream mass flow (kg/h)
m_C	coal mass flow (kg/h)
m_G	raw syngas mass flow (kg/h)
Q_G	raw syngas sensible heat (MJ/h)
Q_S	thermal energy required for steam production (MJ/h)
x_i	molar fraction of species i (dimensionless)
η_{CG}	cold gas efficiency (dimensionless)
η_{HG}	hot gas efficiency (dimensionless)
<u>Acronyms</u>	
CCS	carbon capture and storage
CGD	cold gas desulphurization
CHP	combined heat and power
CoE	cost of electricity

COHYGEN coal-to-hydrogen generation research and development project

CtE	coal-to-liquids
DME	dymethylether (CH ₃ -O-CH ₃)
ENEA	Italian National Agency for Energy and Environment
ESP	electrostatic precipitator
FT	Fisher-Tropsch
GAIA	greenhouse-gas absorption in amine-based solvents bench-scale plant
HT	high temperature
ICE	internal combustion engine
IGCC	integrated gasification combined cycle
LHV	lower heating value (MJ/kg)
LT	low temperature
MDEA	methyldiethanolamine $(CH_3N(C_2H_4OH)_2)$
MEA	monoethanolamine ((CH ₂ CH ₂ OH)NH ₂)
MeOH	methanol (CH ₃ OH)
MOSCA	metal oxides for sulphur compounds adsorption bench-scale plant
PCC	pulverized coal combustion power plant
PID	proportional-integral-derivate controller
PSA	pressure swing adsorption
PZ	piperazine ($C_4H_{10}N_2$)
SBCR	slurry bubble column reactor
SN	stoichiometric number
tar	topping atmospheric residue
WGS	water-gas shift conversion
XRF	X-ray fluorescence

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