Sotacarbo coal-to-hydrogen pilot plant: project development and plant analysis

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Abstract

Nowadays, the increase in energy demand and the interest in the environment preservation, have improved the attention toward hydrogen production through coal gasification, owing to the remarkable advantages offered by this technology in pollution control and greenhouse gases-emissions monitoring.

To this aim, Sotacarbo, with Ansaldo Ricerche, ENEA and the University of Cagliari, is developing a pilot plant for hydrogen production from Sulcis coal gasification. The project, characterized by a total cost of about 12 millions euros, has been funded by the Italian Ministry of Education, University and Research and by the European Commission.

The pilot plant, which has been recently set up in the Sotacarbo Coal Research Centre located in Sardinia, includes two fixed-bed Wellman-Galusha gasifiers (a 700 kg/h pilot gasifier and a 35 kg/h laboratory-scale gasifier), fed up with high and low sulphur coals, and a syngas treating process, which is composed by a raw-gas cleaning section, an advanced integrated water-gas shift and CO_2 removal unit and the hydrogen separation unit. In particular, the raw gas cleaning section includes a hot- and a cold-gas desulphurization process, in order to compare their performances.

This paper reports a detailed description of the research project. In particular, the plant configuration and the main goals of the experimental campaigns are described, together with a hint on the main building and management problems.

Introduction

Otherwise oil and natural gas, which main fields are confined in a relatively small area [1], 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]. Moreover, the advanced in development of clean coal technologies, allows an environmental-friendly use of coal, in particular for power generation.

Among clean coal technologies, gasification is particularly interesting since it allows both power generation (mainly by using integrated gasification combined cycles power plants, IGCC) and clean fuels production, with a particular reference to hydrogen.

All over the world, gasification processes, due to the low flexibility of synthesis gas (syngas) production, are, so far, mainly used in large-scale IGCC power plants in order to supply base energy load. But in a short-term future, the possibility to use syngas to produce

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hydrogen could make gasification technologies very interesting for medium and small-scale industrial application.

As to this possibility, Sotacarbo, together with Ansaldo Ricerche, ENEA and the Department of Mechanical Engineering of the University of Cagliari, is developing an integrated gasification process for combined production of hydrogen and electrical energy, to be used in medium and small-scale commercial plants. The research project, called COHYGEN (Coal to Hydrogen Generation), concerns the development of a gasification and syngas treatment pilot plant, which is located in the Sotacarbo Research Centre in Carbonia, in Sardinia island (Italy). The plant includes a pilot-scale (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 production. The research project is co-funded by the Italian Ministry of Education, University and Research (MIUR) and the total cost is estimated in about 12 million euros.

The Research Centre and the Laboratories

A part of the funding (about 1.5 M€) is dedicated to the construction of the new Sotacarbo Research Centre, which is equipped with advanced laboratories to support the experimental campaigns on the experimental facilities.

The Research Centre covers a surface of about 2500 m^2, whose about 850 m^2 are dedicated to the laboratories, which are equipped with a series of advanced instruments selected to support the experimental campaign of the gasification pilot plant and of other experimental facilities that will be developed in the next years.

In particular, the Sotacarbo laboratories are equipped with all the instrumentation for the coal mixture preparation and analysis (crushers, mills, particle size distribution analyzers, calorimeters, spectrometers instruments for fuel proximate and ultimate analysis, etc.), for the definition of properties (like porosity) of catalysts or sorbents, for liquid and gas analysis (gas-chromatographs, spectrometers, pHmeters, etc.) and so on.

The Sotacarbo coal-to-hydrogen pilot plant

In order to test different plant solutions and different operating conditions, a very flexible and simple layout for the pilot plant has been considered. The experimental results obtained by means of this pilot plant will constitute the basis of the second phase of the research project, which will lead to the realization of the demonstrative unit of the Sotacarbo coal-to-hydrogen process.

The current layout of the Sotacarbo pilot plant includes two fixed-bed up-draft Wellman-Galusha gasifiers: a 700 kg/h pilot gasifier and a 35 kg/h laboratory-scale gasifier. 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 700 kg/h pilot gasifier is the optimization of the gasification process and the definition of start-up and shut-down procedures, the 35 kg/h laboratory-scale plant is used to develop the syngas treatment process for hydrogen production. Therefore, while the pilot plant is 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 (schematically represented in figure 1).

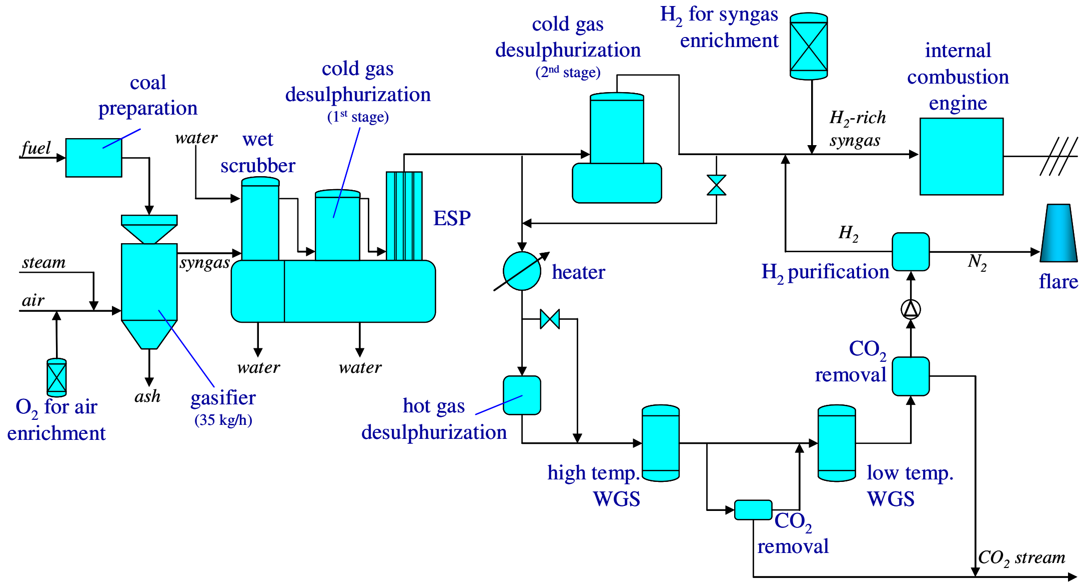

Figure 1 *– Simplified scheme of the Sotacarbo laboratory-scale experimental plant.*

In the Sotacarbo laboratory-scale plant, 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 uses a soda-based solvent) and an 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 a cold gas desulphurization process, whereas the secondary stream, that is the remaining 20% of the produced syngas, is sent to a hot gas desulphurization process, which is followed by the hydrogen production section.

In particular, the main syngas treatment line is constituted by the second cold gas desulphurization stage, based on a hydrogen sulphide (H_2S) absorption process (which uses a mixture of soda and sodium hypochlorite, diluted in water, as solvent), directly followed by the power generation section, represented by a syngas-feed internal combustion engine.

The secondary syngas treatment 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 dry hot gas desulphurization process (which employs metal oxide-based sorbents), an integrated CO-shift and CO_2 absorption system and a hydrogen purification system, based on the PSA (Pressure Swing Adsorption) technology. 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.

The laboratory-scale gasifier is designed to operate with enriched air (simply by using an oxygen bottle) and will be experimentally evaluated the possibility to operate a 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; otherwise, it is possible to operate the hydrogen enrichment simply by using a hydrogen bottle located upstream the engine.

Furthermore, a suitable portion of the clean syngas produced by the cold desulphurization process (second stage) can be split upstream the diesel engine and fed to the integrated CO-shift and CO_2 absorption system, in order to compare the performances of both cold and hot syngas desulphurization processes for hydrogen production.

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.

The gasification process

As already mentioned, the Sotacarbo pilot plant includes two up-draft fixed-bed Wellman-Galusha gasifiers, developed and manufactured by Ansaldo Ricerche S.p.A. In particular, the 700 kg/h pilot gasifier is used for the optimization of the gasification process and for the definition of start-up and shut-down procedures (required to scale-up and commercialize the gasification process), while the 35 kg/h laboratory-scale gasifier is a kind of syngas generator used to feed the syngas treatment line.

For the feed of both gasifiers, coal, which will be bought in big bags for the experimental tests, is drawn out from the storage area through a heaver and, through a tackle, charged in a particular hopper in order to empty big bags. Then, coal is drawn out from this hopper, weighted and sent to the two gasifiers through a conveyer belt.

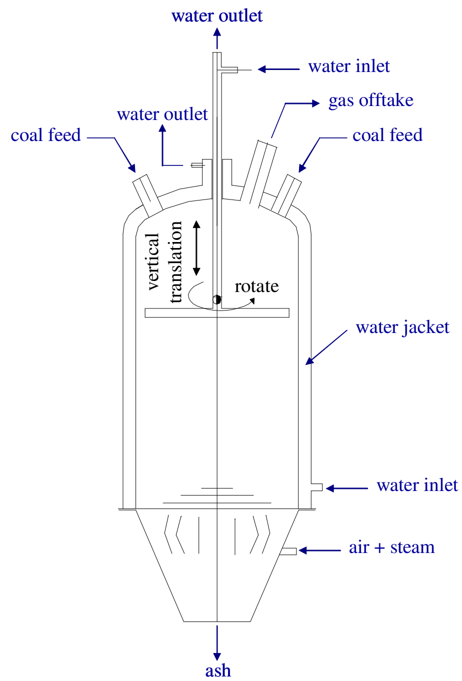

Figure 2 *– Simplified scheme of 700 kg/h pilot gasifier [3].*

The 700 kg/h (5 MW_{th}) pilot gasifier (figures 2 and 3) is characterized by four main operating zones, where the coal drying, devolatilization, gasification and combustion processes take place. As the coal flows downwards, it is heated by the hot raw gas that moves upwards, coming from the gasification and combustion zones [4-5]. The gasification agents (air and steam) are introduced into the reactor near the bottom, so that they are pre-heated by cooling the bottom ash, which are removed through the coal grate.

In order to distribute the coal as uniformly as possible and optimize the gasification process, the gasifier is equipped with an internally cooled stirrer (in order to keep a low metal temperature), which is characterized by two degrees of freedom: an axial rotation and a vertical translation. Furthermore, the gasifier is equipped with a cooling water jacket, in order to operate an accurate temperature control.

Since the 700 kg/h pilot gasifier does not include the syngas desulphurization section, it will be only fuelled with low sulphur coals (with a sulphur content lower than 0.5-0.6 % wt.).

The 35 kg/h (200 kW_{th}) laboratory-scale gasifier can be consider as a syngas generator for the feeding of the treatment line. With respect to the pilot gasifier, it is characterized by a simplified structure: the reactor does


Figure 3 *– Pilot gasifier during the plant construction phase*

	High sulphur coal	Low sulphur coal
Carbon	53.17	65.84
Hydrogen	3.89	3.71
Nitrogen	1.29	1.50
Sulphur	5.98	0.55
Oxygen	6.75	5.35
Chlorine	0.10	0.05
Moisture	11.51	8.00
Ash	17.31	15.00
LHV [MJ/kg]	20.83	24.79

***Table 1** – Sulcis and South African coal ultimate analysis [6].*

	High sulphur coal	Low sulphur coal
Input data		
Mass flow [kg/h]	35.0	35.0
Steam/coal mass ratio	0.26	0.34
O_2/coal mass ratio	0.44	0.56
O_2 molar fraction	0.2073	0.2073
Oxidant inlet temp. [°C]	120	120
Steam inlet temp. [°C]	120	120
Syngas composition		
CO	0.2867	0.3165
CO_2	0.0235	0.0120
H_2	0.1698	0.2016
N_2	0.3975	0.4078
CH_4	0.0274	0.0087
H_2S	0.0137	0.0009
COS	0.0007	0.0001
Ar	0.0047	0.0049
H_2O	0,0760	0.0475
Gasifier performances		
Syngas mass flow [kg/h]	105.12	127.02
Syngas vol. flow [Nm^3/h]	102.2	126.8
Syngas LHV [MJ/kg]	6.6414	6.5015
Cold gas efficiency	93.65	93.26
Syngas outlet temp. [°C]	288.5	332.3
Gasifier yield [Nm^3/kg]	2.70	3.45

***Table 2** – Main gasification parameters for Sulcis and South African coal [6].*

not include the internally cooled stirrer and the water jacket (the walls are covered with a refractory material) and the ash discharged system is simplified.

The laboratory-scale gasifier will be fuelled by several coals. In particular, a high-sulphur Sulcis coal and a low-sulphur South African coal (whose ultimate analyses are shown in table 1) have been choice for the experimental campaigns. Moreover, in the laboratory-scale gasifier, the possibility to enrich the gasification air with oxygen and to operate a co-gasification of coal with biomass and wastes will be investigated.

In table 2 are shown the main performances of the gasification section, evaluated starting from a gasification equilibrium model developed by the Department of Mechanical Engineering of the University of Cagliari [6].

Syngas cooling and depulverization

The raw syngas coming from the laboratory-scale plant is sent to the cooling and depulverization system (figure 4). This system is firstly composed by a wet scrubber, which operates the syngas cooling to about 50 °C and a first dust and tar removal. Downwards the wet scrubber, cold syngas is sent to a first cold gas desulphurization stage, which operates the removal of a small amount of hydrogen sulphide in order to protect the electrostatic precipitator (ESP). The latter allows a fine depulverization and tar removal, in order to assure the best operating conditions of the downwards equipments.

***Figure 4** – Syngas cooling and depulverization system.*

The power generation line

The laboratory-scale plant includes two kind of syngas desulphurization systems, both characterized by two stages of absorption.

According to the design conditions, 80% of the depulverized syngas from the ESP is sent to the second cold gas desulphurization stage, in order to reduce the hydrogen sulphide concentration below the maximum values allowed by the CO-shift conversion processes. As a matter of fact, the catalysts commonly used by the CO-shift reactors can be poisoned by H_2S concentrations above about 50-100 ppm (that is lower than the typical emission standards). Is interesting to notice that the lower amounts of the COS (carbonyl sulphide) are mainly removed by means of the raw gas wet scrubber.

Both the cold syngas desulphurization stages are based on a conventional chemical-physical H_2S absorption process, carried out by a liquid solvent. In particular, the first stage uses, as a solvent, sodium hydroxide diluted in water, while the second stage absorption process is based on a mixture of sodium hydroxide, sodium hypochlorite and water (the second stage absorber has been designed in order to allow some experimental tests with other solvents, like methyl-diethanolamine, MDEA, which is highly selective for hydrogen sulphide [7]). The liquid solvent is continuously recycled to the absorber and an automatic control system regulates the acidity of the solvent solution in order to maintain the pH at about 10.5-11.0.

Downwards the second cold gas desulphurization stage, clean syngas is sent to the power generation section, constituted by a 30 kW gas-feed internal combustion engine. In particular, the fuel gas can be enriched in its energy content by mixing with hydrogen produced in the dedicated line of the plant or, eventually, by using an hydrogen bottle.

The advanced hot-gas treatment line

In order to develop a small-scale commercial plant (where global efficiency plays an important role), a hot gas desulphurization process will also be tested in the Sotacarbo pilot plant; in fact, even if these processes are still far from a massive industrial application, they are extremely simple in their plant configuration and management; moreover, hot syngas desulphurization processes allow to improve the efficiency of the coal gasification plant due to the absence of a deep syngas cooling process.

In the Sotacarbo laboratory-scale plant, about 20% of the syngas produced by the gasification and cooling and depulverization sections is compressed to 1.4 bar, heated to about 400-500 °C (depending of the particular kind of selected metal oxides based sorbent) and sent to the hot syngas desulphurization system. The latter includes two identical reactors which can operate in series or parallel configuration [8]. The reactors have been designed in order to assure a final concentration of sulphur compounds lower than 20 ppm.

In order to produce a hydrogen-rich fuel, a two-stage catalytic CO-shift process, with an intermediate carbon dioxide absorption stage and a final CO_2 removal process (figure 5) has been selected. At the design conditions, the integrated process is fed by the syngas exiting from the hot gas desulphurization process; however,

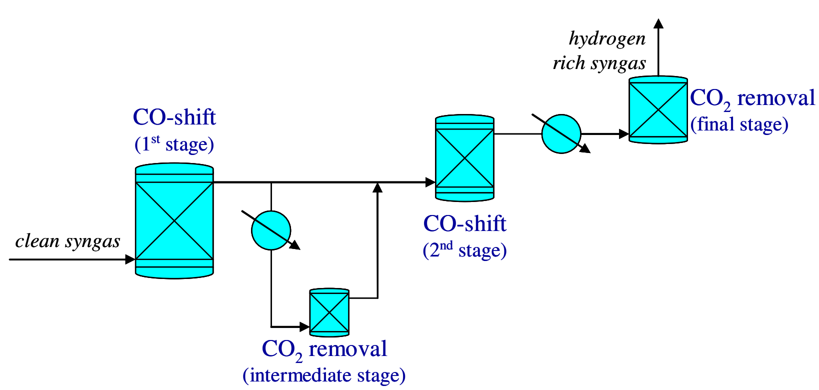

Figure 5 *– Integrated water-gas shift conversion and CO_2 removal system [9].*

this process can also be fed by a portion of the syngas treated by the cold gas desulphurization process (see figure 1).

This integrated configuration has been selected in order to maximize the carbon monoxide conversion into CO_2, for a future use of the hydrogen-rich fuel in a high efficiency power generation section (mainly based on fuel cells).

The two CO_2 removal stages (figure 6) carry out an absorption of carbon dioxide with a solution of water and monoethanolamine (MEA) at an operating temperature of about 30 °C, in an advanced reactor which uses two innovative membranes for the gas diffusion in the liquid phase and for the liquid/gas separation downwards the absorption process. In order to minimize the steam consumption and optimize heat exchanges in the integrated process, only a portion (about 50%) of syngas from the first CO-shift stage is sent to the intermediate CO_2 absorption section.

Figure 6 *– CO_2 absorption reactor*

In order to assess the capabilities of the pilot plant to produce a hydrogen-rich fuel for fuelling advanced power generation systems (as micro gas turbines and fuel cells), the Sotacarbo pilot plant will be equipped with an hydrogen purification system. In particular, a PSA (pressure swing adsorption) system will be selected for the current plant configuration, but other kind of processes will be considered for the plant scale-up. The system includes two identical reactors, since when one reactor operates as absorber, the other is regenerated with the injection of a hydrogen-rich stream.

Plant control and management system

The experimental facility is managed and monitored by a semi-automatic system, in particular for the start-up, the shut-down and the operating procedures.

Moreover, the plant is equipped with an automatic alarm system, which is based on measures of temperature, flow, pressure and level, and on an oxygen concentration in the raw syngas downwards the gasifier. This alarm system has been designed according with the ISO standards.

The sampling system

In order to support the experimental tests, the Sotacarbo facility 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, both pilot and laboratory-scale gasifiers are 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 two different micro gas chromatographs and to evaluate the concentration of the main chemical compounds (CO_2, H_2, CO, CH_4, N_2, H_2S, COS) in the selected stream. Even if this system doesn't allow a real-time monitoring of syngas composition, it gives a detailed measure of syngas composition every about 5 minutes, which represents a time range negligible with respect to the plant dynamics.

Plant building and management

Due to the innovative feature of some equipments of the Sotacarbo experimental facility, the design of each component is the result of a detailed analysis carried out in strict collaboration between the designers, the producers and the users of the plant. This collaboration allows, in some cases, to adjust some commercial components to the needs of the experimental plant.

Risk analysis

During the design phase of the experimental facility, a risk analysis for every component of the plant has been carried out, in order to assess the main risks connected to the use of each equipment. As a consequence, the preventive actions to reduce the risk probabilities have been defined for the plant design and building.

In general, the adopted safety requirements respect two main guidelines: to prevent the potential formation of explosive atmosphere or, if it is not possible, to avoid the primer in such atmosphere. Where this prevention strategy has been adopted, the reduction of risks of explosion has been based on the assumption of design criteria, of process choice and of regulation and control strategies selected in order to avoid the contemporary presence, in each section of the plant, of fuel, oxygen and primer. To that end, a detailed analysis of the operation of each plant equipment has been executed, considering the behaviour of each component singularly and in its interconnections with the overall plant.

The plant design has been developed by applying a series of safety technical rules, with particular reference to the ATEX Directives 94/9/CE and 99/92/CE for the equipments or protective systems located in the zones characterized by a potential risk of explosion. The ATEX rules, which are a directives adopted by the European Union (EU), provide for the first time essential health and safety requirements for non-electrical equipment intended for use in potentially explosive atmospheres and equipment intended for use in environments which are potentially explosive due to dust hazards and protective systems and for devices intended for use outside explosive atmospheres which are required for or contribute to the safe functioning of equipment or protective systems with respect to risks of explosion [10].

In application of the mentioned ATEX Directives, the potential sources of the explosion event have been analyzed considering two different categories of events: events correlated to the ordinary plant operation and events correlated with plant malfunctioning and breakdown. As for the first kind of events, the plant design has been developed in order to avoid their happening. On the other hand, as for the events correlated with plant malfunctioning, direct or indirect redundancies have been considered and operating procedures have been defined in order to guarantee the safety of the plant.

Licensing procedures

During the design and the construction of the Sotacarbo experimental facility, three different kind of problems have been faced, regarding the safety of the plant, the licensing procedures, and the main technical requirements.

As for the licensing procedures, the main authorization have been released by the local section of Vigili del Fuoco (the Italian Fire Department) and by the ASL (the local public healthcare administration), besides the building licences released from the Carbonia Town Administration.

Pollutant emissions

Even if the rules that regulates the pollutant emission for the experimental plants are less restrictive than those referred to the commercial power plants, the interest to shortly commercialize the Sotacarbo coal-to-hydrogen process suggests to design the experimental facility according with the emission limit of a medium scale commercial plant.

The pilot gasifier, which is not equipped by a syngas purification system, will be fed only with high quality coals (with a sulphur concentration lower than 1%). Therefore, the concentration of sulphur oxides in flue gas is about 1500 mg/Nm^3 (dry-basis), while the concentration of nitrogen oxides and dust is estimated in about 600 and 150 mg/Nm^3, respectively.

On the contrary, the laboratory-scale gasifier is equipped by two different syngas purification lines for the removal of sulphur compounds, dust and tars. This allows to feed the plant even with low rank fuels, like high sulphur Sulcis coal, obtaining pollutant concentration in flue gas more and more lower than the current emission limits.

Fuels, chemicals and wastes

As for coal supplying, the Sotacarbo experimental plant will be tested in particular with high sulphur Sulcis coal and low sulphur coal (like South African coal), but can also be fed with mixtures of coal, biomass and wastes. In any case, the fuel is supplied in big bags (each containing about 1 m^3 of coal, corresponding to about 800 kg).

The main chemicals used in the plant are the solvents (sodium hydroxide and sodium hypochlorite) for the two low temperature desulphurization processes, which will be supplied at high concentration in proper small-size containers, and the monoethanolamine for the CO_2 capture system, which is supplied diluted in water in proper “cubitainers” characterized by a total volume of about 1.5 m^3.

As for the wastes, the gasification ash and the liquids are temporarily stored in metal hopper and tanks, respectively. Then the wastes are transported through proper vehicles to third companies authorized for the permanent disposal.

Costs

The global cost for the design and build-up of the experimental facility and its auxiliary equipments and works is shown in table 3. In particular, the cost for the experimental facility includes the two gasifiers, the syngas treatment line and the coal handling and feeding system. As for the experimental campaign, a global cost of about 900 000 € has been preliminarily estimated.

	Cost [k€]
Experimental facility	1 860
B.o.P. (balance of plant)	200
Civil works	600
Laboratories	550
TOTAL	***3 210***

***Table 3** – Main costs of the experimental facility and auxiliaries.*

Conclusions

In order to release energy production from oil and natural gas, coal gasification can play a very important role, in particular for the remarkable advantages offered by this technologies in pollution control and greenhouse gases emissions monitoring. Moreover, the increasing interest for hydrogen production can make gasification processes very interesting, due to the possibility to produce this gas from low rank fuel, as coal, biomass and wastes.

In this scenario, Sotacarbo, together with Ansaldo Ricerche, ENEA and the University of Cagliari, is engaged in the COHYGEN project in order to develop an integrated gasification and syngas treatment process for combined hydrogen and electrical energy production for small and medium scale industrial applications. To this aim, an experimental facility has been designed and build-up in order to test the performances of each component of the process and to select the most efficient plant configuration.

In particular, the experimental facility includes two different coal gasification plants: a 700 kg/h (5 MW_{th}) pilot gasifier and a 35 kg/h (200 kW_{th}) laboratory-scale gasifier; the last one is equipped with a syngas treatment line for syngas cleaning and for hydrogen and electrical energy production.

In particular, the pilot plant will be used to optimize the gasification process and to define the start-up and the shut-down procedures, whereas the laboratory-scale plant has been designed in order to test some conventional and advanced gas treatment process with a syngas produced from low-rank fuels.

The experimental campaigns, which will start in the next months, will be finalized to collect a series of operating data which allows a plant optimization and scale-up and the preliminary design of a commercial-scale coal-to-hydrogen plant.

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